



TITLE:

# On some free boundary problems for the Navier-Stokes equations in unbounded domains (Mathematical Analysis in Fluid and Gas Dynamics)

AUTHOR(S):

Shibata, Yoshihiro

---

CITATION:

Shibata, Yoshihiro. On some free boundary problems for the Navier-Stokes equations in unbounded domains (Mathematical Analysis in Fluid and Gas Dynamics). 数理解析研究所講究録 2018, 2070: 85-106

ISSUE DATE:

2018-04

URL:

<http://hdl.handle.net/2433/241990>

RIGHT:

# On some free boundary problems for the Navier-Stokes equations in unbounded domains

Yoshihiro SHIBATA\*

Department of Mathematics, Waseda University

This note deals with the global wellposedness of some free boundary problems for the Navier-Stokes equations in unbounded domains. A technical issue is how to combine the maximal regularity estimates for the highest order terms with the decay estimates for the lower order terms of solutions to the linearized equations. It does not seem to be popular enough compared with the Navier-Stokes equations with non-slip boundary conditions. In the later case, the Navier-Stokes equations are just parabolic ones, and so the decay properties for the Stokes equations with non-slip boundary conditions are enough. On the other hand, in the free boundary conditions case, after transforming an unknown time dependent domain to some known fixed one, the problem becomes a system of quasilinear parabolic equations with nonlinear boundary conditions, and so some combinations of the maximal regularity estimates for the highest order terms with the decay estimates for the lower order terms are necessary to prove the global well-posedness at least for small initial data, which is not well-known compared with the non-slip boundary conditions. In this note, I would like to show some combinations, which does not seem to be optimal/best possible, but is enough to prove the global well-posedness for small initial data. Notice that in the bounded domain case, exponentially stable maximal regularity estimates are obtained, and so it is not necessary to consider combinations mentioned above.

## 1 One Phase Problem in an Exterior Domain

### 1.1 Problem and Global in Time Unique Existence Theorem

We first consider the following free boundary problem for the Navier-Stokes equations:

$$\begin{cases} \partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{v} - \operatorname{Div}(\mu \mathbf{D}(\mathbf{v}) - \mathbf{p} \mathbf{I}) = 0, & \operatorname{div} \mathbf{v} = 0 & \text{for } x \in \Omega_t, 0 < t < T, \\ (\mu \mathbf{D}(\mathbf{v}) - \mathbf{p} \mathbf{I}) \mathbf{n}_t = 0, & V_n = \mathbf{v} \cdot \mathbf{n}_t = 0 & \text{for } x \in \Gamma_t, 0 < t < T, \\ \mathbf{v}|_{t=0} = \mathbf{v}_0 & & \text{for } x \in \Omega_0. \end{cases} \quad (1)$$

Unknowns are the domain  $\Omega_t$  with the boundary  $\Gamma_t$ , and the functions  $\mathbf{v}(x, t) = (v_1, \dots, v_N)^\top$ , where  $M^\top$  denotes the transposed  $M$ , and  $\mathbf{p}(x, t)$ ,  $x \in \Omega_t$ . The domain  $\Omega_0 = \Omega$  is an exterior domain in the  $N$ -dimensional Euclidean space  $\mathbb{R}^N$  ( $N \geq 2$ ) with the  $C^2$  boundary  $\Gamma$ . By  $\mathbf{n}_t = (n_{t1}, \dots, n_{tN})^\top$  we mean the exterior normal to  $\Gamma_t$ , and  $V_n$  is the velocity of the evolution of  $\Gamma_t$  in the normal direction.  $\mathbf{D}(\mathbf{v}) = \nabla \mathbf{v} + (\nabla \mathbf{v})^\top$  is the doubled rate-of-strain tensor whose  $(i, j)^{\text{th}}$  component is  $\partial_i v_j + \partial_j v_i$ ,  $\partial_i = \partial/\partial x_i$ .  $\mu$  is a positive constant describing the viscosity coefficient. We assume that the mass density is one. Moreover,  $\mathbf{I}$  is the  $N \times N$  identity matrix, and

$$\mathbf{v} \cdot \mathbf{n}_t = \sum_{j=1}^N v_j n_{tj}, \quad \nabla \mathbf{p} = (\partial_1 \mathbf{p}, \dots, \partial_N \mathbf{p})^\top, \quad \partial_t \mathbf{v} = \left( \frac{\partial v_1}{\partial t}, \dots, \frac{\partial v_N}{\partial t} \right)^\top, \quad \operatorname{div} \mathbf{v} = \sum_{j=1}^N \frac{\partial v_j}{\partial x_j},$$

---

\*mailing address: Department of Mathematics, Waseda University, Ohkubo 3-4-1, Shinjuku-ku, Tokyo 169-8555, Japan.  
e-mail address: yshibata@waseda.jp

Adjunction faculty member in the Department of Mechanical Engineering and Materials Science, University of Pittsburgh.  
Partially supported by Top Global University Project, JSPS Grant-in-aid for Scientific Research (A) 17H0109, and JSPS program of the Japanese-Germann Graduate Program

$$\text{Div } \mathbf{K} = \left( \sum_{j=1}^N \frac{\partial K_{1j}}{\partial x_j}, \dots, \sum_{j=1}^N \frac{\partial K_{Nj}}{\partial x_j} \right)^\top, \quad (\mathbf{v} \cdot \nabla) \mathbf{v} = \left( \sum_{j=1}^N v_j \frac{\partial v_1}{\partial x_j}, \dots, \sum_{j=1}^N v_j \frac{\partial v_N}{\partial x_j} \right)^\top,$$

where  $\mathbf{K}$  is the  $N \times N$  matrix of functions whose  $(i, j)^{\text{th}}$  component is  $K_{ij}$ .

If we use the Hanzawa transform to transform  $\Omega_t$  to some fixed domain, we have to require  $W_q^{3-1/q}$  regularity of the height function  $\rho$  representing  $\Gamma_t$ . However, this regularity is obtained by surface tension, that is the Laplace-Beltrami operator on  $\Gamma_t$ . In this section, we consider the case where the surface tension is not taken into account. Thus, we can not obtain  $W_q^{3-1/q}$  regularity of the height function, and so the Hanzawa transform can not be used in the present case. Another method is to use the Lagrange transform. However, we can not expect the exponential decay for the solutions of the Stokes equations with free boundary conditions, because  $\Omega$  is an unbounded domain. We will have only polynomial decay properties of solutions of the Stokes equations with free boundary conditions, which is not sufficient to control the term: first derivatives of  $\int_0^t \mathbf{u}(y, s) ds$  times the second derivatives of  $\mathbf{u}$ , where  $\mathbf{u}$  is the velocity field in the Lagrange coordinates  $\{y\}$ .

To overcome this difficulty, the idea here is to use the Lagrange transform only near the boundary. Let  $R$  be a positive number for which  $\mathcal{O} = \mathbb{R}^N \setminus \Omega \subset B_{R/2}$ . Here and in the following,  $B_L$  denotes the ball with radius  $L$ . Let  $\kappa \in C_0^\infty(B_{2R})$  equal one in  $B_R$ . Let  $\mathbf{u}(y, t)$  be the velocity field in the Lagrange coordinates  $\{y\}$ . We consider a partial Lagrange transform:

$$x = X_{\mathbf{u}}(y, t) = y + \int_0^t \kappa(y) \mathbf{u}(y, s) ds. \quad (2)$$

Assume that

$$\int_0^T \|\kappa(\cdot) \mathbf{u}(\cdot, s)\|_{H_\infty^1(\Omega)} ds \leq \delta. \quad (3)$$

As symbols, here and in the following, for any domain  $G$  in  $\mathbb{R}^N$ ,  $L_q(G)$ ,  $H_q^m(G)$ , and  $B_{q,p}^s(G)$  denote the standard Lebesgue, Sobolev, and Besov spaces on  $G$ , and  $\|\cdot\|_{L_q(G)}$ ,  $\|\cdot\|_{H_q^m(G)}$ , and  $\|\cdot\|_{B_{q,p}^s(G)}$  denote their respective norms.

In the assumption (3),  $\delta > 0$  is a small number that will be chosen in such a way that several conditions hold. For example, we choose  $0 < \delta < 1/2$ , so that the map  $x = X_{\mathbf{u}}(y, t)$  is injective for each  $t \in (0, T)$ . Let

$$\Psi(y, t) = \int_0^t \kappa(y) \mathbf{u}(y, s) ds = (\Psi_1(y, t), \dots, \Psi_N(y, t))^\top.$$

Let  $y = X_{\mathbf{u}}^{-1}(x, t)$  be the inverse of the transformation:  $x = X_{\mathbf{u}}(y, t)$  given in (2). Setting

$$\Omega_t = \{x = X_{\mathbf{u}}(y, t) \mid y \in \Omega\}, \quad \Gamma_t = \{x = X_{\mathbf{u}}(y, t) \mid y \in \Gamma\},$$

$\mathbf{v}(x, t) = \mathbf{u}(X_{\mathbf{u}}^{-1}(x, t), t)$ , and  $\mathbf{p}(x, t) = \mathbf{q}(X_{\mathbf{u}}^{-1}(x, t), t)$ , we then see that Eq. (1) is transformed to

$$\begin{cases} \partial_t \mathbf{u} - \text{Div}(\mu \mathbf{D}(\mathbf{u}) - \mathbf{q} \mathbf{I}) = \mathbf{f}(\mathbf{u}), & \text{in } \Omega \times (0, T), \\ \text{div } \mathbf{u} = g(\mathbf{u}) = \text{div } \mathbf{g}(\mathbf{u}) & \text{in } \Omega \times (0, T), \\ (\mu \mathbf{D}(\mathbf{u}) - \mathbf{q} \mathbf{I}) \mathbf{n} = \mathbf{h}(\mathbf{u}) & \text{on } \Gamma \times (0, T), \\ \mathbf{v}|_{t=0} = \mathbf{u}_0 & \text{in } \Omega. \end{cases} \quad (4)$$

Here,  $\mathbf{u}_0 = \mathbf{v}_0$ ,  $\mathbf{n}$  is the unit outer normal to  $\Gamma$ , and  $\mathbf{f}(\mathbf{u})$ ,  $g(\mathbf{u})$ ,  $\mathbf{g}(\mathbf{u})$  and  $\mathbf{h}(\mathbf{u})$  are nonlinear terms, the exact formulas of which will be given below.

As symbols, we use bold lowercase letters to denote  $N$ -vectors and bold capital letters to denote  $N \times N$  matrices. For an  $N$  vector  $\mathbf{a}$ ,  $\mathbf{a}_i$  denotes the  $i^{\text{th}}$  component of  $\mathbf{a}$  and for an  $N \times N$  matrix  $\mathbf{A}$ ,  $\mathbf{A}_{ij}$  denotes the  $(i, j)^{\text{th}}$  component of  $\mathbf{A}$ , and moreover, the  $N \times N$  matrix whose  $(i, j)^{\text{th}}$  component is  $K_{ij}$  is written as  $(K_{ij})$ . For any two  $N \times N$  matrices  $\mathbf{A}$  and  $\mathbf{B}$ ,  $\mathbf{A} : \mathbf{B}$  is defined by  $\mathbf{A} : \mathbf{B} = \sum_{i,j=1}^N \mathbf{A}_{ij} \mathbf{B}_{ij}$ . For any  $N$ -vector of functions,  $\mathbf{w} = (w_1, \dots, w_N)^\top$ ,  $\nabla \mathbf{w}$  is the  $N \times N$  matrix of functions with  $(\nabla \mathbf{w})_{ij} = \partial_j w_i$ , that is

$$\nabla \mathbf{w} = \begin{pmatrix} \partial_1 w_1 & \partial_2 w_1 & \cdots & \partial_N w_1 \\ \partial_1 w_2 & \partial_2 w_2 & \cdots & \partial_N w_2 \\ \vdots & \vdots & \ddots & \vdots \\ \partial_1 w_N & \partial_2 w_N & \cdots & \partial_N w_N \end{pmatrix}.$$

Let  $\partial x/\partial y$  be the Jacobi matrix of the transformation (2). We choose  $\delta > 0$  so small that the inverse matrix of  $\partial x/\partial y$  exists, and therefore there exists an  $N \times N$  matrix  $\mathbf{V}_0(\mathbf{k})$  of  $C^\infty$  functions defined on  $|\mathbf{k}| < \delta$  such that  $\mathbf{V}_0(0) = 0$  and

$$\left(\frac{\partial x}{\partial y}\right)^{-1} = \mathbf{I} + \mathbf{V}_0(\nabla \Psi(y, t)). \quad (5)$$

Here and in the following,  $\mathbf{k} = (k_{ij})$  and  $k_{ij}$  are the variables corresponding to  $\partial_i \Psi_j = \int_0^t \partial_i (\kappa \mathbf{u}_j) ds$ . Let  $V_{0ij}(\mathbf{k}) = \mathbf{V}_0(\mathbf{k})_{ij}$  and  $\nabla_z = (\partial/\partial z_1, \dots, \partial/\partial z_N)^\top$  for  $z = x$  and  $y$ . We then have

$$\nabla_x = (\mathbf{I} + \mathbf{V}_0(\mathbf{k}))\nabla_y, \quad \frac{\partial}{\partial x_i} = \sum_{j=1}^N (\delta_{ij} + V_{0ij}(\mathbf{k})) \frac{\partial}{\partial y_j}. \quad (6)$$

Thus,  $\mathbf{D}(\mathbf{v}) = \mathbf{D}(\mathbf{u}) + \mathcal{D}_{\mathbf{D}}(\mathbf{k})\nabla \mathbf{u}$  with

$$\mathbf{D}(\mathbf{u})_{ij} = \frac{\partial u_i}{\partial y_j} + \frac{\partial u_j}{\partial y_i}, \quad (\mathcal{D}_{\mathbf{D}}(\mathbf{k})\nabla \mathbf{u})_{ij} = \sum_{k=1}^N \left( V_{0jk}(\mathbf{k}) \frac{\partial u_i}{\partial y_k} + V_{0ik}(\mathbf{k}) \frac{\partial u_j}{\partial y_k} \right). \quad (7)$$

We next consider  $\operatorname{div} \mathbf{v}$ . By (6), we have

$$\operatorname{div}_x \mathbf{v} = \sum_{j=1}^N \frac{\partial v_j}{\partial x_j} = \sum_{j,k=1}^N (\delta_{jk} + V_{0jk}(\mathbf{k})) \frac{\partial u_j}{\partial y_k} = \operatorname{div}_y \mathbf{u} + \mathbf{V}_0(\mathbf{k}) : \nabla \mathbf{u}.$$

Let  $J$  be the Jacobian of the transformation (2). Choosing  $\delta > 0$  small enough, we may assume that  $J = J(\mathbf{k}) = 1 + J_0(\mathbf{k})$ , where  $J_0(\mathbf{k})$  is a  $C^\infty$  function defined for  $|\mathbf{k}| < \sigma$  such that  $J_0(0) = 0$ . To obtain another representation formula of  $\operatorname{div}_x \mathbf{v}$ , we use the inner product  $(\cdot, \cdot)_{\Omega_t}$ . As symbols, here and in the following for any domain  $G \subset \mathbb{R}^N$  and its boundary  $\partial G$ ,  $(\mathbf{u}, \mathbf{v})_G$  and  $(\mathbf{u}, \mathbf{v})_{\partial G}$  denote inner products on  $G$  and  $\partial G$ , respectively, that is

$$(\mathbf{u}, \mathbf{v})_G = \int_G \mathbf{u} \cdot \mathbf{v} dx, \quad (\mathbf{u}, \mathbf{v})_{\partial G} = \int_{\partial G} \mathbf{u} \cdot \mathbf{v} ds,$$

where  $ds$  denotes the surface element on the boundary  $\partial G$ .

For any test function  $\varphi \in C_0^\infty(\Omega_t)$ , we set  $\psi(y) = \varphi(x)$ . We then have

$$\begin{aligned} (\operatorname{div}_x \mathbf{v}, \varphi)_{\Omega_t} &= -(\mathbf{v}, \nabla \varphi)_{\Omega_t} = -(J\mathbf{u}, (\mathbf{I} + \mathbf{V}_0)\nabla_y \psi)_{\Omega} = (\operatorname{div} ((\mathbf{I} + \mathbf{V}_0^\top)J\mathbf{u}), \psi)_{\Omega} \\ &= (J^{-1} \operatorname{div} ((\mathbf{I} + \mathbf{V}_0^\top)J\mathbf{u}), \varphi)_{\Omega_t}. \end{aligned}$$

Summing up, we have obtained

$$\operatorname{div}_x \mathbf{v} = \operatorname{div}_y \mathbf{u} + \mathbf{V}_0(\mathbf{k}) : \nabla \mathbf{u} = J^{-1}(\operatorname{div}_y \mathbf{u} + \operatorname{div}_y (J\mathbf{V}_0(\mathbf{k})^\top \mathbf{u})), \quad (8)$$

and so

$$J \operatorname{div}_y \mathbf{u} + J\mathbf{V}_0(\mathbf{k}) : \nabla \mathbf{u} = \operatorname{div}_y \mathbf{u} + \operatorname{div}_y (J\mathbf{V}_0(\mathbf{k})^\top \mathbf{u}).$$

In particular,

$$J_0 \operatorname{div} \mathbf{u} + J\mathbf{V}_0(\mathbf{k}) : \nabla \mathbf{u} = \operatorname{div} (J\mathbf{V}_0(\mathbf{k})^\top \mathbf{u}). \quad (9)$$

To derive the transformation of the momentum equation in (1), we first observe that

$$\sum_{j=1}^N \frac{\partial}{\partial x_j} (\mu \mathbf{D}(\mathbf{v})_{ij} - \mathfrak{p} \delta_{ij}) = \sum_{j,k=1}^N \mu (\delta_{jk} + V_{0jk}) \frac{\partial}{\partial y_k} (\mathbf{D}(\mathbf{u})_{ij} + (\mathcal{D}_{\mathbf{D}}(\mathbf{k})\nabla \mathbf{u})_{ij}) - \sum_{j=1}^N (\delta_{ij} + V_{0ij}) \frac{\partial \mathfrak{q}}{\partial y_j}. \quad (10)$$

where we have used (7). Since

$$\frac{\partial}{\partial t} [v_i(y + \Psi(y, t), t)] = \frac{\partial v_i}{\partial t}(x, t) + \sum_{j=1}^N \kappa(y) u_j(y, t) \frac{\partial v_i}{\partial x_j}(x, t),$$

we have

$$\frac{\partial v_i}{\partial t} = \frac{\partial u_i}{\partial t} - \sum_{j,k=1}^N \kappa u_j (\delta_{jk} + V_{0jk}) \frac{\partial u_i}{\partial y_k},$$

and therefore,

$$\frac{\partial v_i}{\partial t} + \sum_{j=1}^N v_j \frac{\partial v_i}{\partial x_j} = \frac{\partial u_i}{\partial t} + \sum_{j,k=1}^N (1 - \kappa) u_j (\delta_{jk} + V_{0jk}(\mathbf{k})) \frac{\partial u_i}{\partial y_k}. \quad (11)$$

Putting (10) and (11) together gives

$$\begin{aligned} 0 &= \frac{\partial u_i}{\partial t} + \sum_{j,k=1}^N (1 - \kappa) u_j (\delta_{jk} + V_{0jk}(\mathbf{k})) \frac{\partial u_i}{\partial y_k} \\ &\quad - \mu \sum_{j,k=1}^N (\delta_{ij} + V_{0jk}(\mathbf{k})) \frac{\partial}{\partial y_k} (\mathbf{D}(\mathbf{u})_{ij} + (\mathcal{D}_{\mathbf{D}}(\mathbf{k}) \nabla \mathbf{u})_{ij}) - \sum_{j=1}^N (\delta_{ij} + V_{0ij}(\mathbf{k})) \frac{\partial \mathbf{q}}{\partial y_j}. \end{aligned}$$

Since  $(\mathbf{I} + \nabla \Psi)(\mathbf{I} + \mathbf{V}_0) = (\partial x / \partial y)(\partial y / \partial x) = \mathbf{I}$ ,

$$\sum_{i=1}^N (\delta_{mi} + \partial_m \Psi_i) (\delta_{ij} + V_{0ij}(\mathbf{k})) = \delta_{mj},$$

and so we have

$$\begin{aligned} &\sum_{i=1}^N (\delta_{mi} + \partial_m \Psi_i) \left( \frac{\partial u_i}{\partial t} + \sum_{j,k=1}^N (1 - \kappa) u_j (\delta_{jk} + V_{0jk}(\mathbf{k})) \frac{\partial u_i}{\partial y_k} \right) \\ &\quad - \mu \sum_{i,j,k=1}^N (\delta_{mi} + \partial_m \Psi_i) (\delta_{jk} + V_{0jk}(\mathbf{k})) \frac{\partial}{\partial y_k} (\mathbf{D}(\mathbf{u})_{ij} + (\mathcal{D}_{\mathbf{D}}(\mathbf{k}) \nabla \mathbf{u})_{ij}) - \frac{\partial \mathbf{q}}{\partial y_m} = 0. \end{aligned}$$

Thus, changing  $i$  to  $\ell$  and  $m$  to  $i$ , we define an  $N$ -vector of functions  $\mathbf{f}(\mathbf{u})$  by

$$\begin{aligned} \mathbf{f}(\mathbf{u})_i &= - \sum_{j,k=1}^N (1 - \kappa) u_j (\delta_{jk} + V_{0jk}(\mathbf{k})) \frac{\partial u_i}{\partial y_k} \\ &\quad - \sum_{\ell=1}^N \partial_i \Psi_\ell \left( \frac{\partial u_\ell}{\partial t} + \sum_{j,k=1}^N (1 - \kappa) u_j (\delta_{jk} + V_{0jk}(\mathbf{k})) \frac{\partial u_\ell}{\partial y_k} \right) \\ &\quad + \mu \left( \sum_{j=1}^N \frac{\partial}{\partial y_j} (\mathcal{D}_{\mathbf{D}}(\mathbf{k}) \nabla \mathbf{u})_{ij} + \sum_{j,k=1}^N V_{0jk}(\mathbf{k}) \frac{\partial}{\partial y_k} (\mathbf{D}(\mathbf{u})_{ij} + (\mathcal{D}_{\mathbf{D}}(\mathbf{k}) \nabla \mathbf{u})_{ij}) \right. \\ &\quad \left. + \sum_{j,k,\ell=1}^N \partial_i \Psi_\ell (\delta_{jk} + V_{0jk}(\mathbf{k})) \frac{\partial}{\partial y_k} (\mathbf{D}(\mathbf{u})_{\ell j} + (\mathcal{D}_{\mathbf{D}}(\mathbf{k}) \nabla \mathbf{u})_{\ell j}) \right). \end{aligned} \quad (12)$$

And also, from (8) and (9) we have

$$g(\mathbf{u}) = -(J_0(\mathbf{k}) \operatorname{div} \mathbf{u} + (1 + J_0(\mathbf{k})) \mathbf{V}_0(\mathbf{k}) : \nabla \mathbf{u}), \quad \mathbf{g}(\mathbf{u}) = -(1 + J_0(\mathbf{k})) \mathbf{V}_0(\mathbf{k})^\top \mathbf{u}. \quad (13)$$

Recall that

$$\Gamma_t = \{x = y + \Psi(y, t) + \xi(t) \mid y \in \Gamma\} \quad (t \in (0, T)).$$

Since

$$0 = \mathbf{n} \cdot d\mathbf{y} = \mathbf{n} \cdot \left( \frac{\partial y}{\partial x} dx \right) = \mathbf{n} \cdot ((\mathbf{I} + \mathbf{V}_0(\mathbf{k})) dx) = ((\mathbf{I} + \mathbf{V}_0(\mathbf{k}))^\top \mathbf{n}) \cdot dx$$

on  $\Gamma$ , we have

$$\mathbf{n}_t = \frac{(\mathbf{I} + \mathbf{V}_0(\mathbf{k}))^\top \mathbf{n}}{|(\mathbf{I} + \mathbf{V}_0(\mathbf{k}))^\top \mathbf{n}|}. \quad (14)$$

Putting (7) and (14) together gives

$$\begin{aligned} 0 &= (\mu \mathbf{D}(\mathbf{v}) - \mathbf{p} \mathbf{I}) \mathbf{n}_t |(\mathbf{I} + \mathbf{V}_0(\mathbf{k})^\top) \mathbf{n}| \\ &= \mu (\mathbf{D}(\mathbf{u}) + \mathcal{D}_{\mathbf{D}}(\mathbf{k}) \nabla \mathbf{u}) (\mathbf{I} + \mathbf{V}_0(\mathbf{k})^\top) \mathbf{n} - \mathbf{q} (\mathbf{I} + \mathbf{V}_0(\mathbf{k})^\top) \mathbf{n}. \end{aligned}$$

Since  $(\mathbf{I} + (\nabla \Psi)^\top)(\mathbf{I} + \mathbf{V}_0(\mathbf{k})^\top) = \mathbf{I}$ , we have

$$(\mathbf{I} + (\nabla \Psi)^\top) \mu (\mathbf{D}(\mathbf{u}) + \mathcal{D}_{\mathbf{D}}(\mathbf{k}) \nabla \mathbf{u}) (\mathbf{I} + \mathbf{V}_0(\mathbf{k})^\top) \mathbf{n} - \mathbf{q} \mathbf{n} = 0.$$

Thus,

$$\begin{aligned} \mathbf{h}(\mathbf{u}) &= -\mu \{ \mathbf{D}(\mathbf{u}) \mathbf{V}_0(\mathbf{k})^\top \mathbf{n} + (\mathcal{D}_{\mathbf{D}}(\mathbf{k}) \nabla \mathbf{u}) (\mathbf{I} + \mathbf{V}_0(\mathbf{k})^\top) \mathbf{n} \\ &\quad + (\nabla \Psi)^\top (\mathbf{D}(\mathbf{u}) + \mathcal{D}_{\mathbf{D}}(\mathbf{k}) \nabla \mathbf{u}) (\mathbf{I} + \mathbf{V}_0(\mathbf{k})^\top) \mathbf{n} \}. \end{aligned} \quad (15)$$

The main result of this section is the following theorem that shows the unique existence theorem of global in time solutions of Eq.(4) and asymptotics as  $t \rightarrow \infty$ .

**Theorem 1.** *Let  $N \geq 3$  and let  $q_1$  and  $q_2$  be exponents such that  $\max(N, \frac{2N}{N-2}) < q_2 < \infty$  and  $1/q_1 = 1/q_2 + 1/N$ . Let  $b$  and  $p$  be numbers defined by*

$$b = \frac{3N}{2q_2} + \frac{1}{2}, \quad p = \frac{2q_2(1+\sigma)}{q_2 - N} \quad (16)$$

*with some very small positive number  $\sigma$ . Then, there exists an  $\epsilon > 0$  such that if initial data  $\mathbf{u}_0 \in B_{q_2, p}^{2(1-1/p)}(\Omega)^N \cap B_{q_1/2, p}^{2(1-1/p)}(\Omega)^N$  satisfies the compatibility condition:*

$$\operatorname{div} \mathbf{u}_0 = 0 \quad \text{in } \Omega, \quad \mathbf{D}(\mathbf{u}_0) \mathbf{n} - \langle \mathbf{D}(\mathbf{u}_0) \mathbf{n}, \mathbf{n} \rangle \mathbf{n} = 0 \quad \text{on } \Gamma, \quad (17)$$

*and the smallness condition:*

$$\|\mathbf{u}_0\|_{B_{q_2, p}^{2(1-1/p)}} + \|\mathbf{u}_0\|_{B_{q_1/2, p}^{2(1-1/p)}} \leq \epsilon, \quad (18)$$

*then Eq. (4) admits unique solutions  $\mathbf{u}$  and  $\mathbf{q}$  with*

$$\mathbf{u} \in L_p((0, \infty), H_{q_2}^2(\Omega)^N) \cap H_p^1((0, \infty), L_{q_2}(\Omega)^N), \quad \mathbf{q} \in L_p((0, \infty), H_{q_2}^1(\Omega) + \hat{H}_{q_2, 0}^1(\Omega)),$$

*possessing the estimate  $\|\mathbf{u}\|_\infty \leq C\epsilon$  with*

$$\begin{aligned} [\mathbf{u}]_T &= \left\{ \int_0^T \langle s \rangle^b \|\mathbf{u}(\cdot, s)\|_{H_\infty^1(\Omega)}^p ds \right. \\ &\quad + \int_0^T \langle s \rangle^{(b-\frac{N}{2q_1})} \|\mathbf{u}(\cdot, s)\|_{H_{q_1}^1(\Omega)}^p ds + \left( \sup_{0 < s < T} \langle s \rangle^{\frac{N}{2q_1}} \|\mathbf{u}(\cdot, s)\|_{L_{q_1}(\Omega)}^p \right. \\ &\quad \left. \left. + \int_0^T \langle s \rangle^{(b-\frac{N}{2q_2})} (\|\mathbf{u}(\cdot, s)\|_{H_{q_2}^2(\Omega)} + \|\partial_t \mathbf{u}(\cdot, s)\|_{L_{q_2}(\Omega)})^p ds \right) \right\}^{1/p}. \end{aligned}$$

*Here,  $\langle s \rangle = (1 + s^2)^{\frac{1}{2}}$  and  $C$  is a constant that is independent of  $\epsilon$ .*

**Remark 2.** Let  $p' = p/(p-1)$ , that is  $1/p' = 1 - 1/p$ . And then,

$$\frac{1}{p'} = \frac{(1+2\sigma)q_2 + N}{2q_2(1+\sigma)}.$$

We choose  $\sigma > 0$  small enough in such a way that the following relations hold:

$$\begin{aligned} 1 < q_1 < 2, \quad \frac{N}{q_1} > b > \frac{1}{p'}, \quad \left(\frac{N}{q_1} - b\right)p > 1, \quad \left(b - \frac{N}{2q_2}\right)p > 1, \quad b \geq \frac{N}{2q_1}, \\ b \geq \frac{N}{q_2}, \quad \left(\frac{N}{2q_2} + \frac{1}{2}\right)p' < 1, \quad bp' > 1, \quad \left(b - \frac{N}{2q_2}\right)p' > 1, \quad \frac{N}{q_2} + \frac{2}{p} < 1. \end{aligned} \quad (19)$$

**Remark 3.** The exponent  $q_2$  is used to control the nonlinear terms, and so  $q_2$  is chosen in such a way that  $N < q_2 < \infty$ . Let

$$\frac{1}{q_1} = \frac{1}{N} + \frac{1}{q_2}, \quad \frac{1}{q_3} = \frac{1}{q_1} + \frac{1}{q_2}. \quad (20)$$

We require that  $q_1 > 2$  and  $q_3 > 1$  in the proof of Theorem 1, so that  $q_2 > \frac{2N}{N-2}$ . Thus, we have assumed that

$$\max(N, \frac{2N}{N-2}) < q_2 < \infty.$$

**Remark 4.** If we choose  $\delta > 0$  in (3), then  $x = X_{\mathbf{u}}(y, t)$  becomes a diffeomorphism with suitable regularity from  $\Omega$  onto  $\Omega_t$ , and so the original problem (1) is globally well-posed.

#### Further Notation

We further use the following symbols throughout the paper. For any  $N$ -vectors  $\mathbf{a}$  and  $\mathbf{b}$ , let

$$\mathbf{a} \cdot \mathbf{b} = \langle \mathbf{a}, \mathbf{b} \rangle = \sum_{j=1}^N \mathbf{a}_j \mathbf{b}_j, \quad \mathbf{a}_\tau = \mathbf{a} - \langle \mathbf{a}, \mathbf{n} \rangle \mathbf{n}.$$

Given  $1 < q < \infty$ , let  $q' = q/(q-1)$ . For a Banach space  $X$  with norm  $\|\cdot\|_X$ , let  $X^d = \{(f_1, \dots, f_d) \mid f_i \in X \ (i = 1, \dots, d)\}$ , and write the norm of  $X^d$  as simply  $\|\cdot\|_X$ , which is defined by  $\|f\|_X = \sum_{j=1}^d \|f_j\|_X$  for  $f = (f_1, \dots, f_d) \in X^d$ . Let

$$\hat{H}_{q,0}^1(\Omega) = \{\theta \in L_{q,\text{loc}}(\Omega) \mid \nabla \theta \in L_q(\Omega)^N, \theta|_\Gamma = 0\}, \quad H_{q,0}^1(\Omega) = \{u \in H_q^1(\Omega) \mid u|_\Gamma = 0\}.$$

For  $1 \leq p \leq \infty$ ,  $L_p((a, b), X)$  and  $H_p^m((a, b), X)$  denote the standard Lebesgue and Sobolev spaces of  $X$ -valued functions defined on an interval  $(a, b)$ , and  $\|\cdot\|_{L_p((a,b),X)}$ ,  $\|\cdot\|_{H_p^m((a,b),X)}$  denote their respective norms. For  $\theta \in (0, 1)$ ,  $H_p^\theta(\mathbb{R}, X)$  denotes the standard  $X$ -valued Bessel potential space defined by

$$H_p^\theta(\mathbb{R}, X) = \{f \in L_p(\mathbb{R}, X) \mid \|f\|_{H_p^\theta(\mathbb{R}, X)} < \infty\},$$

$$\|f\|_{H_p^\theta(\mathbb{R}, X)} = \left( \int_{\mathbb{R}} \|\mathcal{F}^{-1}[(1 + \tau^2)^{\theta/2} \mathcal{F}[f](\tau)](t)\|_X^p dt \right)^{1/p},$$

where  $\mathcal{F}$  and  $\mathcal{F}^{-1}$  denote the Fourier transform and the inverse Fourier transform, respectively. Let  $C_0^\infty(G)$  be the set of all  $C^\infty$  functions whose supports are compact and contained in  $G$ . The letter  $C$  denotes a generic constant and  $C_{a,b,c,\dots}$  denotes that the constant  $C_{a,b,c,\dots}$  depends on  $a, b, c, \dots$ . The value of  $C$  and  $C_{a,b,c,\dots}$  may change from line to line.

## 1.2 Maximal $L_p$ - $L_q$ regularity theorem and local well-posedness

In this subsection, we state the maximal  $L_p$ - $L_q$  regularity of solutions to the Stokes equations with free boundary condition:

$$\begin{cases} \partial_t \mathbf{u} - \text{Div}(\mu \mathbf{D}(\mathbf{u}) - q \mathbf{I}) = \mathbf{f}, & \text{div } \mathbf{u} = g = \text{div } \mathbf{g} & \text{in } \Omega \times (0, T), \\ (\mu \mathbf{D}(\mathbf{u}) - q \mathbf{I}) \mathbf{n} = \mathbf{h} & & \text{on } \Gamma \times (0, T), \\ \mathbf{u}|_{t=0} = \mathbf{u}_0 & & \text{in } \Omega. \end{cases} \quad (21)$$

We start with the following proposition which was proved in Shibata [9].

**Proposition 5.** *Let  $1 < q < \infty$ . If  $\mathbf{u} \in H_q^1(\Omega)$  satisfies  $\text{div } \mathbf{u} = 0$  in  $\Omega$ , then  $\mathbf{u} \in J_q(\Omega)$ .*

We next consider the weak Dirichlet problem:

$$(\nabla u, \nabla \varphi)_\Omega = (\mathbf{f}, \nabla \varphi)_\Omega \quad \text{for any } \varphi \in \hat{H}_{q',0}^1(\Omega). \quad (22)$$

Then, we know the following fact.

**Proposition 6.** Let  $1 < q < \infty$  and let  $\Omega$  be an exterior domain in  $\mathbb{R}^N$  ( $N \geq 2$ ) with  $C^2$  boundary. Then, the weak Dirichlet problem is uniquely solvable. Namely, for any  $\mathbf{f} \in L_q(\Omega)^N$ , problem (22) admits a unique solution  $u \in \hat{H}_{q,0}^1(\Omega)$  possessing the estimate:  $\|\nabla u\|_{L_q(\Omega)} \leq C\|\mathbf{f}\|_{L_q(\Omega)}$ .

**Remark 7.** (1) This proposition was proved by Pruess and Simonett [6, Section 7.4] and by Shibata [9, Theorem 18] independently.

(2) Let  $\Omega = \mathbb{R}^N \setminus S_1$  and  $\Gamma = S_1$ , where  $S_1$  denotes the unit sphere in  $\mathbb{R}^N$ . Let

$$f(x) = \begin{cases} \ln|x| & N = 2, \\ |x|^{-(N-2)} - 1 & N \geq 3. \end{cases}$$

Then,  $f(x)$  satisfies the strong Dirichlet problem:  $\Delta f = 0$  in  $\Omega$  and  $f|_\Gamma = 0$ . Moreover,  $f \in H_{q,0}^1(\Omega)$  provided that  $q > N/(N-1)$ . However,  $f$  does not satisfy the weak Dirichlet problem:

$$(\nabla f, \nabla \varphi)_\Omega = 0 \quad \text{for any } \varphi \in \hat{H}_{q',0}^1(\Omega).$$

In fact,  $C_0^\infty(\Omega)$  is not dense in  $\hat{H}_{q',0}^1(\Omega)$  when  $1 < q' < N$ . The detailed is discussed in Shibata [9, Appendix A].

Since the weak Dirichlet problem is uniquely solvable, by the result obtained in Shibata [8], we have the following theorem (cf. also Shibata [9]).

**Theorem 8.** Let  $1 < p, q < \infty$  with  $2/p + 1/q \neq 1$  and  $0 < T < \infty$ . Then, there exists a constant  $\gamma_0$  such that the following assertion holds: Let

$$\begin{aligned} \mathbf{u}_0 \in B_{q,p}^{2(1-1/p)}(\Omega)^N, \quad \mathbf{f} \in L_p((0,T), L_q(\Omega)^N), \quad e^{-\gamma t} g \in L_p(\mathbb{R}, H_q^1(\Omega)) \cap H_p^{1/2}(\mathbb{R}, L_q(\Omega)), \\ e^{-\gamma t} \mathbf{g} \in H_p^1(\mathbb{R}, L_q(\Omega)^N), \quad e^{-\gamma t} \mathbf{h} \in H_p^{1/2}(\mathbb{R}, L_q(\Omega)^N) \cap L_p(\mathbb{R}, H_q^1(\Omega)^N) \end{aligned} \quad (23)$$

for any  $\gamma \geq \gamma_0$ , which satisfy the compatibility condition:

$$\operatorname{div} \mathbf{u}_0 = g|_{t=0} \quad \text{in } \Omega \quad (24)$$

and, in addition,

$$(\mu \mathbf{D}(\mathbf{u}_0) \mathbf{n} - \mathbf{h}|_{t=0})_\tau = 0 \quad \text{on } \Gamma \quad (25)$$

provided that  $2/p + 1/q < 1$ . Then, problem (21) admits unique solutions  $\mathbf{u}$  and  $\mathbf{p}$  with

$$\begin{aligned} \mathbf{u} \in L_p((0,T), H_q^2(\Omega)^N) \cap H_p^1((0,T), L_q(\Omega)^N), \\ \mathbf{p} \in L_p((0,T), H_q^1(\Omega) + \hat{H}_{q,0}^1(\Omega)) \end{aligned} \quad (26)$$

satisfying the estimates

$$\begin{aligned} \|\mathbf{u}\|_{L_p((0,T), H_q^2(\Omega))} + \|\partial_t \mathbf{u}\|_{L_p((0,T), L_q(\Omega))} \leq C_\gamma e^{\gamma T} [\|\mathbf{u}_0\|_{B_{q,p}^{2(1-1/p)}(\Omega)} + \|\mathbf{f}\|_{L_p((0,T), L_q(\Omega))} \\ + \|e^{-\gamma t}(g, \mathbf{h})\|_{L_p(\mathbb{R}, H_q^1(\Omega))} + \|e^{-\gamma t}(g, \mathbf{h})\|_{H_p^{1/2}(\mathbb{R}, L_q(\Omega))} + \|e^{-\gamma t} \mathbf{g}\|_{H_p^1(\mathbb{R}, L_q(\Omega))}] \end{aligned} \quad (27)$$

for any  $\gamma \geq \gamma_0$  and for some positive constant  $C$  depending on  $\gamma_0$  but independent of  $\gamma \geq \gamma_0$ .

**Remark 9.** In the case where  $2/p + 1/q < 1$ ,  $\mathbf{D}(\mathbf{u}_0) \in B_{q,p}^{1-2/p}(\Omega)$  and  $1 - 2/p > 1/q$ , and so  $\mathbf{D}(\mathbf{u}_0)|_\Gamma$  exists. However,  $1/p < 1/2$  and  $\mathbf{h} \in H_p^{1/2}(\mathbb{R}, L_q(\Omega)^N)$  implies that  $\mathbf{h}$  is continuous with respect to  $t \in \mathbb{R}$  in the  $L_q(\Omega)$  topology, and so  $\mathbf{h}|_{t=0}$  exists as an element in  $L_q(\Omega)$ , but we do not know whether the trace of  $\mathbf{h}|_{t=0}$  to  $\Gamma$  exists. Thus, we implicitly assume the existence of the trace of  $\mathbf{h}|_{t=0}$  to  $\Gamma$  in (25).

Using Theorem 8 and Banach's fixed point theorem, Shibata [9] proved the following local in time unique existence theorem for Eq. (1).



**Theorem 10.** Let  $2 < p < \infty$ ,  $N < q < \infty$  and  $S > 0$ . Let  $\Omega$  be an exterior domain in  $\mathbb{R}^N$  ( $N \geq 2$ ) whose boundary  $\Gamma$  is a  $C^2$  compact hypersurface. Assume that  $2/p + N/q < 1$ . Then, there exists a time  $T > 0$  depending on  $S$  such that if initial data  $\mathbf{u}_0 \in B_{q,p}^{2(1-1/p)}(\Omega)^N$  satisfies  $\|\mathbf{u}_0\|_{B_{q,p}^{2(1-1/p)}(\Omega)} \leq S$  and the compatibility condition:

$$\operatorname{div} \mathbf{u}_0 = 0 \text{ in } \Omega, \quad (\mathbf{D}(\mathbf{u}_0)\mathbf{n})_\tau = 0 \text{ on } \Gamma, \quad (28)$$

then problem (4) admits a unique solution  $(\mathbf{u}, \mathbf{q})$  with

$$\mathbf{u} \in L_p((0, T), H_q^2(\Omega)^N) \cap H_p^1((0, T), L_q(\Omega)^N), \quad \mathbf{q} \in L_p((0, T), H_q^1(\Omega) + \hat{H}_{q,0}^1(\Omega))$$

possessing the estimate:

$$\|\mathbf{u}\|_{L_p((0, T), H_q^2(\Omega))} + \|\partial_t \mathbf{u}\|_{L_p((0, T), L_q(\Omega))} \leq CS, \quad \int_0^T \|\kappa(\cdot) \mathbf{v}(\cdot, s)\|_{H_\infty^1(\Omega)} ds \leq \delta$$

for some constant  $C > 0$  independent of  $T$  and  $S$ . Here,  $\delta$  is the constant appearing in (3).

### 1.3 A new formulation of Eq. (4)

Let  $T > 0$  and let

$$\mathbf{u} \in H_p^1((0, T), L_q(\Omega)^N) \cap L_p((0, T), H_q^2(\Omega)^N), \quad \mathbf{q} \in L_p((0, T), H_q^1(\Omega) + \hat{H}_{q,0}^1(\Omega)) \quad (29)$$

be solutions of Eq. (4) satisfying the condition (3). We then prove the global in time unique existence theorem by prolonging this local solution to any time interval. To prolong  $\mathbf{u}$  beyond  $(0, T)$ , we need some decay estimates of  $\mathbf{u}$ . For this purpose, we rewrite Eq. (4) in order that the nonlinear terms have suitable decay properties.

In the following, we repeat the argument in Subsec. 1.1. Let

$$a_{ij}(t) = \delta_{ij} + \tilde{a}_{ij}(t), \quad J(t) = 1 + \tilde{J}(t), \quad \ell_{ij}(t) = \delta_{ij} + \tilde{\ell}_{ij}(t) \quad (30)$$

with

$$\begin{aligned} \tilde{a}_{ij}(t) &= V_{0ij} \left( \int_0^t \nabla(\kappa(y) \mathbf{v}(y, s)) ds \right), \quad \tilde{J}(t) = J_0 \left( \int_0^t \nabla(\kappa(y) \mathbf{v}(y, s)) ds \right), \\ \tilde{\ell}_{ij}(t) &= m_{ij} \left( \int_0^t \nabla(\kappa(y) \mathbf{v}(y, s)) ds \right) := \int_0^t \frac{\partial}{\partial y_j} (\kappa(y) u_i(y, t)) ds. \end{aligned} \quad (31)$$

By (6) and (14), we have

$$\begin{aligned} \frac{\partial}{\partial x_j} &= \sum_{j=1}^N a_{ji}(t) \frac{\partial}{\partial y_j}, \quad n_{ti} = d(t) \sum_{j=1}^N a_{ji}(t) n_j, \\ \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} &= \sum_{k=1}^N (a_{kj}(t) \frac{\partial u_i}{\partial y_k} + a_{ki}(t) \frac{\partial u_j}{\partial y_k}) = D_{ij}(\mathbf{u}) + \tilde{D}_{ij}(t) \nabla \mathbf{u} \end{aligned} \quad (32)$$

where  $d(t) = |\mathbf{A}(t)^\top \mathbf{n}| = |(\mathbf{I} + \mathbf{V}_0(\mathbf{k})^\top) \mathbf{n}|$ , and

$$D_{ij}(\mathbf{u}) = \frac{\partial u_i}{\partial y_j} + \frac{\partial u_j}{\partial y_i}, \quad \tilde{D}_{ij}(t) \nabla \mathbf{u} = \sum_{k=1}^N (\tilde{a}_{kj}(t) \frac{\partial u_i}{\partial y_k} + \tilde{a}_{ki}(t) \frac{\partial u_j}{\partial y_k}).$$

Moreover, by (8) we have

$$\operatorname{div} \mathbf{v} = \sum_{j,k=1}^N J(t) a_{kj}(t) \frac{\partial u_j}{\partial y_k} = \sum_{j,k=1}^N \frac{\partial}{\partial y_k} (J(t) a_{kj}(t) u_j). \quad (33)$$

And then, Eq. (4) is written as follows:

$$\left\{ \begin{array}{l} \sum_{i=1}^N \ell_{is}(t)(\partial_t u_i + (1 - \kappa) \sum_{j,k=1}^N u_j a_{kj}(t) \frac{\partial u_i}{\partial y_k}) \\ - \mu \sum_{i,j,k=1}^N \ell_{is}(t) a_{kj}(t) \frac{\partial}{\partial y_k} D_{ij,t}(\mathbf{u}) - \frac{\partial \mathbf{q}}{\partial y_s} = 0 \quad \text{in } \Omega \times (0, T), \\ \sum_{j,k=1}^N J(t) a_{kj}(t) \frac{\partial u_j}{\partial y_k} = \sum_{j,k=1}^N \frac{\partial}{\partial y_k} (J(t) a_{kj}(t) u_j) = 0 \quad \text{in } \Omega \times (0, T), \\ \mu \sum_{i,j,k=1}^N \ell_{is}(t) a_{kj}(t) D_{ij,t}(\mathbf{u}) n_k - \mathbf{q} n_s = 0 \quad \text{on } \Gamma \times (0, T), \\ \mathbf{u}|_{t=0} = \mathbf{u}_0 \quad \text{in } \Omega, \end{array} \right. \quad (34)$$

where  $s$  runs from 1 through  $N$ . Here, we have used the fact that  $(\ell_{ij}) = \mathbf{A}^{-1}$ .

In order to get some decay properties of the nonlinear terms, we write

$$\int_0^t \nabla(\kappa(y) \mathbf{u}(y, s)) ds = \int_0^T \nabla(\kappa(y) \mathbf{u}(y, s)) ds - \int_t^T \nabla(\kappa(y) \mathbf{u}(y, s)) ds.$$

In (31), by the Taylor formula we write

$$\begin{aligned} a_{ij}(t) &= a_{ij}(T) + \mathcal{A}_{ij}(t), & \ell_{ij}(t) &= \ell_{ij}(T) + \mathcal{L}_{ij}(t), \\ D_{ij,t}(\mathbf{u}) &= D_{ij,T}(\mathbf{u}) + \mathcal{D}_{ij}(t) \nabla \mathbf{u}, & J(t) &= J(T) + \mathcal{J}(t) \end{aligned} \quad (35)$$

with

$$\begin{aligned} \mathcal{A}_{ij}(t) &= - \int_0^1 V'_{0ij} \left( \int_0^T \nabla(\kappa(y) \mathbf{u}(y, s)) ds - \theta \int_t^T \nabla(\kappa(y) \mathbf{u}(y, s)) ds \right) d\theta \int_t^T \nabla(\kappa(y) \mathbf{u}(y, s)) ds \\ \mathcal{L}_{ij}(t) &= - \int_t^T \frac{\partial}{\partial y_j} (\kappa(y) u_i(y, s)) ds, \quad \mathcal{D}_{ij}(t) \nabla \mathbf{u} = \sum_{k=1}^N (\mathcal{A}_{kj}(t) \frac{\partial u_i}{\partial y_k} + \mathcal{A}_{ki}(t) \frac{\partial u_j}{\partial y_k}), \\ \mathcal{J}(t) &= - \int_0^1 J'_0 \left( \int_0^T \nabla(\kappa(y) \mathbf{u}(y, s)) ds - \theta \int_t^T \nabla(\kappa(y) \mathbf{u}(y, s)) ds \right) d\theta \int_t^T \nabla(\kappa(y) \mathbf{u}(y, s)) ds, \end{aligned}$$

where  $V'_{0ij}$  and  $J'_0$  are derivatives of  $V_{0ij}$  and  $J_0$  with respect to  $\mathbf{k}$ . By the relation:

$$\sum_{s=1}^N \ell_{is}(T) a_{sm}(T) = \delta_{si}, \quad (36)$$

the first equation in (34) is rewritten as follows:

$$\partial_t u_m - \sum_{j,k=1}^N a_{kj}(T) \frac{\partial}{\partial y_k} (\mu D_{mj,T}(\mathbf{u}) - \delta_{mj} \mathbf{q}) = \tilde{f}_m(\mathbf{u})$$

with

$$\begin{aligned} \tilde{f}_m(\mathbf{u}) &= - \sum_{s=1}^N a_{sm}(T) \left\{ \sum_{i=1}^N \mathcal{L}_{is}(t) \partial_t u_i + \sum_{i,j,k=1}^N (1 - \kappa) \ell_{is}(t) a_{kj}(t) u_j \frac{\partial u_i}{\partial y_k} \right\} \\ &+ \mu \sum_{s=1}^N a_{sm}(T) \left\{ \sum_{i,j,k=1}^N \ell_{is}(T) a_{kj}(T) \frac{\partial}{\partial y_k} (\mathcal{D}_{ij}(t) \nabla \mathbf{u}) + \sum_{i,j,k=1}^N \ell_{is}(T) \mathcal{A}_{kj}(t) \frac{\partial}{\partial y_k} D_{ij,t}(\mathbf{u}) \right\} \\ &+ \sum_{i,j,k=1}^N \mathcal{L}_{is}(t) a_{kj}(t) \frac{\partial}{\partial y_k} D_{ij,t}(\mathbf{u}). \end{aligned} \quad (37)$$

The second equation in (34) is rewritten as

$$\widetilde{\operatorname{div}} \mathbf{u} = \tilde{g}(\mathbf{u}) = \operatorname{div} \tilde{\mathbf{g}}(\mathbf{u})$$

with

$$\begin{aligned} \widetilde{\operatorname{div}} \mathbf{u} &= \sum_{j,k=1}^N J(T) a_{kj}(T) \frac{\partial u_j}{\partial y_k} = \sum_{j,k=1}^N \frac{\partial}{\partial y_k} (J(T) a_{kj}(T) u_j), \\ \tilde{g}(\mathbf{u}) &= \sum_{j,k=1}^N (J(T) \mathcal{A}_{kj}(t) + \mathcal{J}(t) a_{kj}(t)) \frac{\partial u_j}{\partial y_k}, \\ \tilde{g}_k(\mathbf{u}) &= \sum_{j=1}^N (J(T) \mathcal{A}_{kj}(t) + \mathcal{J}(t) a_{kj}(t)) u_j, \quad \tilde{\mathbf{g}}(\mathbf{u}) = (\tilde{g}_1(\mathbf{u}), \dots, \tilde{g}_N(\mathbf{u}))^\top. \end{aligned} \quad (38)$$

And the boundary condition in (34) is rewritten as

$$\sum_{j,k=1}^N a_{kj}(T) (\mu D_{mj,T}(\mathbf{u}) - \delta_{mj} \mathbf{q}) n_k = \tilde{h}_m(\mathbf{u})$$

with

$$\tilde{h}_m(\mathbf{u}) = -\mu \sum_{j,k=1}^N (a_{kj}(T) D_{mj}(t) \nabla \mathbf{u} + \mathcal{A}_{kj}(t) D_{mj,t}(\mathbf{u})) n_k - \mu \sum_{i,j,k,s=1}^N a_{sm}(T) \mathcal{L}_{is}(t) a_{kj}(t) D_{ij,t}(\mathbf{u}) n_k. \quad (39)$$

By (33),

$$\sum_{j,k=1}^N a_{kj}(T) \frac{\partial}{\partial y_k} (\mu D_{mj,T}(\mathbf{u}) - \delta_{mj} \mathbf{q}) = J(T)^{-1} \sum_{j,k=1}^N \frac{\partial}{\partial y_k} (J(T) a_{kj}(T) (\mu D_{mj,T}(\mathbf{u}) - \delta_{mj} \mathbf{q})).$$

Thus, letting

$$\begin{aligned} S_{mk}(\mathbf{u}, \mathbf{q}) &= \sum_{j=1}^N J(T) a_{kj}(T) (D_{mj,T}(\mathbf{u}) - \delta_{mj} \mathbf{q}), \quad \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q}) = (S_{ij}(\mathbf{u}, \mathbf{q})), \\ \tilde{\mathbf{f}}(\mathbf{u}) &= (\tilde{f}_1(\mathbf{u}), \dots, \tilde{f}_N(\mathbf{u}))^\top, \quad \tilde{\mathbf{h}}(\mathbf{u}) = (\tilde{h}_1(\mathbf{u}), \dots, \tilde{h}_N(\mathbf{u}))^\top, \end{aligned}$$

and using (33), we see that  $\mathbf{u}$  and  $\mathbf{q}$  satisfy the following equations:

$$\begin{cases} \partial_t \mathbf{u} - J(T)^{-1} \operatorname{Div} \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q}) = \tilde{\mathbf{f}}(\mathbf{u}) & \text{in } \Omega \times (0, T), \\ \widetilde{\operatorname{div}} \mathbf{u} = \tilde{g}(\mathbf{u}) = \operatorname{div} \tilde{\mathbf{g}}(\mathbf{u}) & \text{in } \Omega \times (0, T), \\ \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q}) \mathbf{n} = J(T) \tilde{\mathbf{h}}(\mathbf{u}) & \text{on } \Gamma \times (0, T), \\ \mathbf{u}|_{t=0} = \mathbf{u}_0 & \text{in } \Omega. \end{cases} \quad (40)$$

This is the new formula of the equations which local in time solutions  $\mathbf{u}$  and  $\mathbf{q}$  of Eq. (4) satisfy. We call Eq. (40) slightly perturbed Stokes equations.

#### 1.4 Slightly perturbed Stokes equations

In this subsection we summarize some results obtained by Shibata [10] concerning the slightly perturbed Stokes equations. Let  $r$  be an exponent such that  $N < r < \infty$ . Let  $a_{ij}(T)$ ,  $\tilde{a}_{ij}(T)$ ,  $J(T)$  and  $\tilde{J}(T)$  be functions defined in (30). We assume that

$$\|(\tilde{a}_{ij}(T), \tilde{J}(T))\|_{L_\infty(\Omega)} + \|\nabla(\tilde{a}_{ij}(T), \tilde{J}(T))\|_{L_r(\Omega)} \leq \sigma \quad (41)$$

with some small constant  $\sigma > 0$ . In the following, we write  $a_{ij}(T)$ ,  $\tilde{a}_{ij}(T)$ ,  $J(T)$  and  $\tilde{J}(T)$  simply by  $a_{ij}$ ,  $\tilde{a}_{ij}$ ,  $J$  and  $\tilde{J}$ , respectively. And also, we write  $\mathbf{A}(T) = (a_{ij}(T))$  by  $\mathbf{A}$ . We want to state the maximal  $L_p$ - $L_q$  regularity and some decay properties of solutions of Eq. (40). To define the solenoidal space for (40), we introduce the weak Dirichlet problem:

$$(\tilde{\nabla} \mathbf{u}, J \tilde{\nabla} \varphi)_\Omega = (\mathbf{f}, J \tilde{\nabla} \varphi)_\Omega \quad \text{for any } \varphi \in \hat{H}_{q',0}^1(\Omega). \quad (42)$$

Here,

$$\tilde{\nabla} \varphi = \left( \sum_{k=1}^N a_{k1} \frac{\partial \varphi}{\partial x_k}, \dots, \sum_{k=1}^N a_{kN} \frac{\partial \varphi}{\partial x_k} \right)^\top = \mathbf{A}^\top \nabla \varphi.$$

Since  $\tilde{a}_{ij}$  and  $\tilde{J}$  vanish outside of  $B_{2R}$ ,  $\widetilde{\operatorname{div}} \mathbf{u} = \operatorname{div} \mathbf{u}$  and  $\tilde{\nabla} \varphi = \nabla \varphi$  in  $\mathbb{R}^N \setminus B_{2R}$ . Thus, by Proposition 6 and (41) with small  $\sigma > 0$ , we have the following result.

**Proposition 11.** *Let  $1 < q \leq r$ . Then, for any  $\mathbf{f} \in L_q(\Omega)^N$  problem (42) admits a unique solution  $\mathbf{u} \in \hat{H}_{q,0}^1(\Omega)$  possessing the estimate:  $\|\nabla \mathbf{u}\|_{L_q(\Omega)} \leq C \|\mathbf{f}\|_{L_q(\Omega)}$ .*

Let  $\tilde{J}(\Omega)$  be the space defined by

$$\tilde{J}(\Omega) = \{\mathbf{u} \in L_q(\Omega) \mid (\mathbf{u}, J \tilde{\nabla} \varphi)_\Omega = 0 \quad \text{for any } \varphi \in \hat{H}_{q',0}^1(\Omega)\}.$$

Given  $\mathbf{f} \in L_q(\Omega)^N$ , let  $\mathbf{u} \in \hat{H}_{q,0}^1(\Omega)$  be a unique solution of the weak Dirichlet problem (42), and then  $\mathbf{f} - \tilde{\nabla} \mathbf{u} \in \tilde{J}_q(\Omega)$ , and so the projection  $\tilde{P} : L_q(\Omega)^N \rightarrow \tilde{J}(\Omega)$  is defined by  $\tilde{P}\mathbf{f} = \mathbf{f} - \tilde{\nabla} \mathbf{u}$ . Obviously,  $\|\tilde{P}\mathbf{f}\|_{L_q(\Omega)} \leq C \|\mathbf{f}\|_{L_q(\Omega)}$ .

We consider the initial problem:

$$\partial_t \mathbf{u} - J(T)^{-1} \operatorname{Div} \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q}) = 0, \quad \widetilde{\operatorname{div}} \mathbf{u} = 0 \quad \text{in } \Omega \times (0, T), \quad \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q}) \mathbf{n}|_\Gamma = 0, \quad \mathbf{u}|_{t=0} = \mathbf{f}. \quad (43)$$

Shibata [10] proved the following theorem.

**Theorem 12.** *Assume that  $N \geq 3$ . Then, there exists a  $\sigma > 0$  such that if the assumption (41) holds, then for any  $q \in (1, r]$ , there exists a  $C^0$  analytic semigroup  $\{T_S(t)\}_{t \geq 0}$  such that for any  $\mathbf{f} \in L_q(\Omega)$ , a unique solution  $\mathbf{u}$  of Eq. (43) is represented by  $\mathbf{u} = T_S(t) \tilde{P}\mathbf{f}$ .*

Moreover, for any  $p \in [q, \infty]$ ,  $\mathbf{f} \in \tilde{J}_q(\Omega)$ , and  $t > 0$  we have the following estimates:

$$\begin{aligned} \|T_S(t) \tilde{P}\mathbf{f}\|_{L_p(\Omega)} &\leq C_{q,p} t^{-\frac{1}{2}(\frac{1}{q} - \frac{1}{p})} \|\mathbf{f}\|_{L_q(\Omega)}, \\ \|\nabla T_S(t) \tilde{P}\mathbf{f}\|_{L_p(\Omega)} &\leq C_{q,p} t^{-\frac{1}{2} - \frac{1}{2}(\frac{1}{q} - \frac{1}{p})} \|\mathbf{f}\|_{L_q(\Omega)}. \end{aligned} \quad (44)$$

If we consider the equations:

$$\begin{cases} \partial_t \mathbf{u} - J^{-1} \operatorname{Div} \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q}) = \mathbf{f}, & \widetilde{\operatorname{div}} \mathbf{u} = 0 & \text{in } \Omega \times (0, T), \\ \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q}) \mathbf{n} = 0 & & \text{on } \Gamma, \\ \mathbf{u}|_{t=0} = 0 & & \text{in } \Omega. \end{cases} \quad (45)$$

Let  $\psi \in \hat{H}_{q,0}^1(\Omega)$  be a solution of the weak Dirichlet problem:

$$(\tilde{\nabla} \psi, J \tilde{\nabla} \varphi)_\Omega = (\mathbf{f}, J \tilde{\nabla} \varphi)_\Omega \quad \text{for any } \varphi \in \hat{H}_{q',0}^1(\Omega).$$

Let  $\mathbf{g} = \mathbf{f} - \tilde{\nabla} \psi$ , and then  $\mathbf{g} \in \tilde{J}_q(\Omega)$  and

$$\|\mathbf{g}\|_{L_q(\Omega)} + \|\nabla \psi\|_{L_q(\Omega)} \leq C \|\mathbf{f}\|_{L_q(\Omega)}.$$

Using this decomposition, we can rewrite Eq. (45) as

$$\begin{cases} \partial_t \mathbf{u} - J^{-1} \operatorname{Div} \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q} - \psi) = \mathbf{g}, & \widetilde{\operatorname{div}} \mathbf{u} = 0 & \text{in } \Omega \times (0, T), \\ \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q} - \psi) \mathbf{n} = 0 & & \text{on } \Gamma, \\ \mathbf{u}|_{t=0} = 0 & & \text{in } \Omega. \end{cases}$$

where we have used the fact that  $\psi|_{\Gamma} = 0$ . By Duhamel's principle, we have

$$\mathbf{u} = \int_0^t T_S(t-s) \mathbf{g}(s) ds = \int_0^t T_S(t-s) \tilde{P} \mathbf{f}(s) ds. \quad (46)$$

This is a solution formula of Eq. (45).

Finally, we consider the equations:

$$\begin{cases} \partial_t \mathbf{u} + \lambda_0 \mathbf{u} - J(T)^{-1} \text{Div} \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q}) = \mathbf{f} & \text{in } \Omega \times (0, T), \\ \widetilde{\text{div}} \mathbf{u} = g = \text{div} \mathbf{g} & \text{in } \Omega \times (0, T), \\ \tilde{\mathbf{S}}(\mathbf{u}, \mathbf{q}) \mathbf{n} = \mathbf{h} & \text{on } \Gamma \times (0, T), \\ \mathbf{u}|_{t=0} = \mathbf{u}_0 & \text{in } \Omega. \end{cases} \quad (47)$$

Let

$$\tilde{\mathbf{n}} = \frac{\mathbf{A}^\top \mathbf{n}}{|\mathbf{A}^\top \mathbf{n}|}, \quad \tilde{\mathbf{D}}(\mathbf{u}) = (D_{ij,T}(\mathbf{u})).$$

Using these symbols, the boundary conditions in (47) is written as follows:

$$(\tilde{\mathbf{D}}(\mathbf{u}) - \mathbf{q} \mathbf{I}) \tilde{\mathbf{n}} = (J(T) |\mathbf{A}^\top \mathbf{n}|)^{-1} \mathbf{h} \quad \text{on } \Gamma \times (0, T).$$

For any  $N$ -vector  $\mathbf{d}$ , let  $\mathbf{d}_\tau = \mathbf{d} - \langle \mathbf{d}, \tilde{\mathbf{n}} \rangle \tilde{\mathbf{n}}$ . The following theorem was proved in Shibata [10].

**Theorem 13.** *Let  $1 < p, q < \infty$  and assume that  $2/p + N/q \neq 1$ . Then, there exist constants  $\sigma > 0$  and  $\lambda_0 > 0$  such that if the assumption (41) holds, then the following assertion holds: Let  $\mathbf{u}_0 \in B_{q,p}^{2(1-1/p)}(\Omega)^N$  be initial data for Eq. (47) and let  $\mathbf{f}, g, \mathbf{g}, d, \mathbf{h}$  be given functions in the right side of Eq. (47) with*

$$\begin{aligned} \mathbf{f} &\in L_p(\mathbb{R}, L_q(\Omega)^N), \quad g \in H_p^1(\mathbb{R}, H_q^1(\Omega)) \cap H_p^{1/2}(\mathbb{R}, L_q(B_R)), \quad \mathbf{g} \in H_p^1(\mathbb{R}, L_q(\Omega)^N), \\ \mathbf{h} &\in H_p^1(\mathbb{R}, H_q^1(\Omega)^N) \cap H_p^{1/2}(\mathbb{R}, L_q(\Omega)^N). \end{aligned}$$

*Assume that the compatibility condition:  $\widetilde{\text{div}} \mathbf{u}_0 = g|_{t=0}$  in  $\Omega$  holds. In addition, the compatibility condition:  $(\mu \tilde{\mathbf{D}}(\mathbf{u}_0))_\tau = (J(T) |\mathbf{A}^\top|)^{-1} \mathbf{h}|_{t=0}_\tau$  on  $\Gamma$  holds provided  $2/p + 1/q < 1$ . Then, problem (47) admits unique solutions  $\mathbf{u}$  and  $\mathbf{q}$  with*

$$\mathbf{u} \in H_p^1((0, T), L_q(\Omega)^N) \cap L_p((0, T), H_q^2(\Omega)^N), \quad \mathbf{q} \in L_p((0, T), H_q^1(\Omega) + \hat{H}_{q,0}^1(\Omega))$$

*possessing the estimate:*

$$\begin{aligned} \|\mathbf{u}\|_{L_p((0,T), H_q^2(\Omega))} + \|\partial_t \mathbf{u}\|_{L_p((0,T), L_q(\Omega))} &\leq C(\|\mathbf{u}_0\|_{B_{q,p}^{2(1-1/p)}(\Omega)} + \|\mathbf{f}\|_{L_p(\mathbb{R}, L_q(\Omega))} \\ &\quad + \|(g, \mathbf{h})\|_{H_p^{1/2}(\mathbb{R}, L_q(\Omega))} + \|(g, \mathbf{h})\|_{L_p(\mathbb{R}, H_q^1(\Omega))} + \|\partial_t \mathbf{g}\|_{L_p(\mathbb{R}, L_q(\Omega))}) \end{aligned} \quad (48)$$

*for some constant  $C$ .*

Since  $\partial_t \langle t \rangle^b \mathbf{u} = \langle t \rangle^b \partial_t \mathbf{u} + b \langle t \rangle^{b-1} \mathbf{u}$ , if  $\mathbf{u}$  and  $\mathbf{q}$  satisfy Eq. (47), then  $\langle t \rangle^b \mathbf{u}$  and  $\langle t \rangle^b \mathbf{q}$  satisfy the equations:

$$\begin{aligned} \partial_t \langle t \rangle^b \mathbf{u} + \lambda_0 \langle t \rangle^b \mathbf{u} - J(T)^{-1} \text{Div} \tilde{\mathbf{S}}(\langle t \rangle^b \mathbf{u}, \langle t \rangle^b \mathbf{q}) \\ = \langle t \rangle^b \mathbf{f} + b \langle t \rangle^{b-1} \mathbf{u} \quad \text{in } \Omega \times (0, T), \\ \widetilde{\text{div}} \langle t \rangle^b \mathbf{u} = \langle t \rangle^b g = \text{div}(\langle t \rangle^b \mathbf{g}) \quad \text{in } \Omega \times (0, T), \\ \tilde{\mathbf{S}}(\langle t \rangle^b \mathbf{u}, \langle t \rangle^b \mathbf{q}) \mathbf{n} = \langle t \rangle^b \mathbf{h} \quad \text{on } \Gamma \times (0, T), \\ \langle t \rangle^b \mathbf{u}|_{t=0} = \mathbf{u}_0 \quad \text{in } \Omega. \end{aligned}$$

Thus, repeated use of Theorem 13 yields that

$$\begin{aligned} \|\langle t \rangle^b \mathbf{u}\|_{L_p((0,T), H_q^2(\Omega))} + \|\langle t \rangle^b \partial_t \mathbf{u}\|_{L_p((0,T), L_q(\Omega))} \\ \leq C(\|\mathbf{u}_0\|_{B_{q,p}^{2(1-1/p)}(\Omega)} + \|\langle t \rangle^b \mathbf{f}\|_{L_p(\mathbb{R}, L_q(\Omega))} + \|(\langle t \rangle^b g, \langle t \rangle^b \mathbf{h})\|_{H_p^{1/2}(\mathbb{R}, L_q(\Omega))} \\ + \|(\langle t \rangle^b g, \langle t \rangle^b \mathbf{h})\|_{L_p(\mathbb{R}, H_q^1(\Omega))} + \|\partial_t \langle t \rangle^b \mathbf{g}\|_{L_p(\mathbb{R}, L_q(\Omega))}), \end{aligned} \quad (49)$$

provided that the right hand side is finite.

### 1.5 The estimate of the nonlinear terms

We state the estimate of  $\tilde{\mathbf{f}}(\mathbf{u})$ ,  $\tilde{g}(\mathbf{u})$ ,  $\tilde{\mathbf{g}}(\mathbf{u})$ , and  $\tilde{\mathbf{h}}(\mathbf{u})$ , which are defined in Subsec. 1.3. To use the estimate (49), we have to extend  $\tilde{g}(\mathbf{u})$ ,  $\tilde{\mathbf{g}}(\mathbf{u})$  and  $\tilde{\mathbf{h}}(\mathbf{u})$  to  $\mathbb{R}$ . Notice that  $\tilde{g}(\mathbf{u})$ ,  $\tilde{\mathbf{g}}(\mathbf{u})$  and  $\tilde{\mathbf{h}}(\mathbf{u})$  vanish at  $t = T$ . Given  $f$  defined on  $(0, T)$  vanishing at  $t = T$ , we define  $e_T[f]$  by

$$e_T[f](t) = \begin{cases} 0 & \text{for } t > T, \\ f(t) & \text{for } 0 < t < T, \\ f(-t) & \text{for } -T < t < 0, \\ 0 & \text{for } t < -T. \end{cases}$$

Notice that  $e_T[f] = f$  on  $(0, T)$ . Then, for  $q = q_1/2$  and  $q = q_2$  we have

$$\begin{aligned} & \| \langle t \rangle^b \tilde{\mathbf{f}}(\mathbf{u}) \|_{L_p((0,T), L_q(\Omega))} + \| \langle t \rangle^b (e_T[\tilde{g}(\mathbf{u})], \langle t \rangle^b e_T[\tilde{J}(T)\mathbf{h}(\mathbf{u})]) \|_{H_p^{1/2}(\mathbb{R}, L_q(\Omega))} \\ & + \| \langle t \rangle^b e_T[\tilde{g}(\mathbf{u})], \langle t \rangle^b e_T[\tilde{J}(T)\mathbf{h}(\mathbf{u})] \|_{L_p(\mathbb{R}, H_q^1(\Omega))} + \| \langle t \rangle^b \partial_t (e_T[\mathbf{h}(\mathbf{u})]) \|_{L_p(\mathbb{R}, L_q(\Omega))} \\ & \leq C(\mathcal{I} + [\mathbf{u}]_T^2), \end{aligned} \quad (50)$$

where  $\mathcal{I} = \|\mathbf{u}_0\|_{B_{q_2,p}^{2(1-1/p)}(\Omega)} + \|\mathbf{u}_0\|_{B_{q_1/2,p}^{2(1-1/p)}(\Omega)}$ . The proof of (50) is given in Shibata [11].

### 1.6 A proof of Theorem 1

Let  $T$  be a positive number  $> 2$ . Then, there exists an  $\epsilon_0 > 0$  depending on  $T$  such that if initial data  $\mathbf{u}_0$  satisfies  $\|\mathbf{u}_0\|_{B_{q_2,p}^{2(1-1/p)}(\Omega)} \leq \epsilon_0$ , then problem (4) admits unique solutions  $\mathbf{u}$  and  $\mathbf{q}$  satisfying the regularity condition (29) and the condition (3). We prolong  $\mathbf{u}$  and  $\mathbf{q}$  to any time interval beyond  $T$ . For this purpose, it suffices to prove that

$$[\mathbf{u}]_T \leq C(\mathcal{I} + [\mathbf{u}]_T^2) \quad (51)$$

for some constant  $C > 0$ . Once obtaining (51), we can show that there exists a small constant  $\epsilon \in (0, \epsilon_0)$  such that if  $\mathcal{I} \leq \epsilon$  then  $[\mathbf{u}]_T \leq C\epsilon$  for some constant  $C > 0$  independent of  $\epsilon$ , and so we can prolong  $\mathbf{u}$  to any time interval beyond  $(0, T)$ . In the following, we use the results stated in Subsec. 1.4 with  $r = q_2$  and Subsec. 1.5.

As was seen in Subsec. 1.3,  $\mathbf{u}$  and  $\mathbf{q}$  satisfy Eq. (40). To estimate  $\mathbf{u}$ , we divide  $\mathbf{u}$  and  $\mathbf{q}$  into two parts as  $\mathbf{u} = \mathbf{w} + \mathbf{v}$ , and  $\mathbf{q} = \mathbf{r} + \mathbf{p}$ , where  $\mathbf{w}$  and  $\mathbf{r}$  are solutions of the equations:

$$\begin{cases} \partial_t \mathbf{w} + \lambda_0 \mathbf{w} - J(T)^{-1} \text{Div} \tilde{\mathbf{S}}(\mathbf{w}, \mathbf{r}) = \tilde{\mathbf{f}}(\mathbf{u}) & \text{in } \Omega \times (0, T), \\ \widetilde{\text{div}} \mathbf{w} = e_T[\tilde{g}(\mathbf{u})] = \text{div } e_T[\tilde{\mathbf{g}}(\mathbf{u})] & \text{in } \Omega \times (0, T), \\ \tilde{\mathbf{S}}(\mathbf{w}, \mathbf{r}) = e_T[J(T)\tilde{\mathbf{h}}(\mathbf{u})] & \text{on } \Gamma \times (0, T), \\ \mathbf{w}|_{t=0} = \mathbf{u}_0 & \text{in } \Omega, \end{cases} \quad (52)$$

and  $\mathbf{v}$  and  $\mathbf{p}$  are solutions of the equations:

$$\begin{cases} \partial_t \mathbf{v} - J(T)^{-1} \text{Div} \tilde{\mathbf{S}}(\mathbf{v}, \mathbf{p}) = -\lambda_0 \mathbf{w} & \text{in } \Omega \times (0, T), \\ \widetilde{\text{div}} \mathbf{v} = 0 & \text{in } \Omega \times (0, T), \\ \tilde{\mathbf{S}}(\mathbf{v}, \mathbf{p}) = 0 & \text{on } \Gamma \times (0, T), \\ \mathbf{v}|_{t=0} = 0 & \text{in } \Omega. \end{cases} \quad (53)$$

Concerning the estimate of  $\mathbf{w}$ , applying (49) and using estimate (50), we have

$$[\mathbf{w}]_T \leq C(\mathcal{I} + [\mathbf{u}]_T^2). \quad (54)$$

We next consider  $\mathbf{v}$ . By (46), we have

$$\mathbf{v}(\cdot, t) = -\lambda_0 \int_0^t T_S(t-s) \tilde{P} \mathbf{w}(\cdot, s) ds. \quad (55)$$

Using the estimate (44) yields that

$$\begin{aligned} \|\nabla^j \mathbf{v}(\cdot, t)\|_{L_r(\Omega)} &\leq C_{r, \tilde{q}_1} \int_0^{t-1} (t-s)^{-\frac{j}{2} - \frac{N}{2}(\frac{1}{\tilde{q}_1} - \frac{1}{r})} \|\mathbf{w}(\cdot, s)\|_{L_{\tilde{q}_1}(\Omega)} ds \\ &\quad + C_{r, \tilde{q}_2} \int_{t-1}^t (t-s)^{-\frac{j}{2} - \frac{N}{2}(\frac{1}{\tilde{q}_2} - \frac{1}{r})} \|\mathbf{w}(\cdot, s)\|_{L_{\tilde{q}_2}(\Omega)} ds \end{aligned} \quad (56)$$

for  $j = 0, 1$ , for any  $t > 1$  and for any indices  $r, \tilde{q}_1$  and  $\tilde{q}_2$  such that  $1 < \tilde{q}_1, \tilde{q}_2 \leq r \leq \infty$  and  $\tilde{q}_1, \tilde{q}_2 \leq q_2$ , where  $\nabla^0 \mathbf{v} = \mathbf{v}$  and  $\nabla^1 \mathbf{v} = \nabla \mathbf{v}$ .

Recall that  $T > 2$ . In what follows, we prove that

$$\left( \int_2^T \langle t \rangle^b \|\mathbf{v}(\cdot, t)\|_{H_\infty^1(\Omega)}^p dt \right)^{1/p} \leq C(\mathcal{I} + [\mathbf{u}_T^2]), \quad (57)$$

$$\sup_{2 \leq t \leq T} \langle t \rangle^{\frac{N}{2q_1}} \|\mathbf{v}(\cdot, t)\|_{L_{q_1}(\Omega)} \leq C(\mathcal{I} + [\mathbf{u}_T^2]), \quad (58)$$

$$\left( \int_2^T \langle t \rangle^{b - \frac{N}{2q_1}} \|\mathbf{v}(\cdot, t)\|_{H_{q_1}^1(\Omega)}^p dt \right)^{1/p} \leq C(\mathcal{I} + [\mathbf{u}_T^2]), \quad (59)$$

$$\left( \int_2^T \langle t \rangle^{b - \frac{N}{2q_2}} \|\mathbf{v}(\cdot, t)\|_{L_{q_2}(\Omega)}^p dt \right)^{1/p} \leq C(\mathcal{I} + [\mathbf{u}_T^2]). \quad (60)$$

By (56) with  $r = \infty, \tilde{q}_1 = q_1/2$  and  $\tilde{q}_2 = q_2$ ,

$$\|\mathbf{v}(\cdot, t)\|_{H_\infty^1(\Omega)} \leq C \int_0^t \|T_S(t-s) \tilde{\mathbf{P}} \mathbf{w}(\cdot, s)\|_{H_\infty^1(\Omega)} ds = C(I_\infty(t) + II_\infty(t) + III_\infty(t))$$

with

$$\begin{aligned} I_\infty(t) &= \int_0^{t/2} (t-s)^{-\frac{N}{q_1}} \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds, \\ II_\infty(t) &= \int_{t/2}^{t-1} (t-s)^{-\frac{N}{q_1}} \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds, \\ III_\infty(t) &= \int_{t-1}^t (t-s)^{-\frac{N}{2q_2} - \frac{1}{2}} \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)} ds. \end{aligned}$$

Since

$$\begin{aligned} I_\infty(t) &\leq (t/2)^{-\frac{N}{q_1}} \left( \int_0^{t/2} \langle s \rangle^{-bp'} ds \right)^{1/p'} \left( \int_0^{t/2} \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)}^p ds \right)^{1/p} \\ &\leq C(bp' - 1)^{-1/p'} (\mathcal{I} + [\mathbf{u}_T^2]) t^{-\frac{N}{q_1}} \end{aligned}$$

as follows from the condition:  $bp' > 1$  in (19), by the condition:  $(\frac{N}{q_1} - b)p > 1$  in (19), we have

$$\int_2^T \langle t \rangle^b I_\infty(t)^p dt \leq C \int_2^T \langle t \rangle^{-\left(\frac{N}{q_1} - b\right)p} dt (\mathcal{I} + [\mathbf{u}_T^2])^p \leq C \left( \left( \frac{N}{q_1} - b \right) p - 1 \right)^{-1} (\mathcal{I} + [\mathbf{u}_T^2])^p.$$

By Hölder's inequality,

$$\begin{aligned} \langle t \rangle^b II_\infty(t) &\leq C \int_{t/2}^{t-1} (t-s)^{-\frac{N}{q_1}} \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds \\ &\leq C \left( \int_{t/2}^{t-1} (t-s)^{-\frac{N}{q_1}} ds \right)^{1/p'} \left( \int_{t/2}^{t-1} (t-s)^{-\frac{N}{q_1}} \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)}^p ds \right)^{1/p} \\ &\leq C \left( \frac{N}{q_1} - 1 \right)^{-1/p'} \left( \int_{t/2}^{t-1} (t-s)^{-\frac{N}{q_1}} \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)}^p ds \right)^{1/p} \end{aligned}$$

because  $N/q_1 = N/q_2 + 1 > 1$ . By the change of integration order and (54),

$$\begin{aligned} \int_2^T (< t >^b II_\infty(t))^p dt &\leq C \left( \frac{N}{q_1} - 1 \right)^{-\frac{p}{p'}} \int_2^T dt \int_{t/2}^{t-1} (t-s)^{-\frac{N}{q_1}} (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)})^p ds \\ &\leq C \left( \frac{N}{q_1} - 1 \right)^{-\frac{p}{p'}} \int_1^{T-1} (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)})^p ds \int_{s+1}^{2s} (t-s)^{-\frac{N}{q_1}} dt \\ &\leq C \left( \frac{N}{q_1} - 1 \right)^{-p} (\mathcal{I} + [\mathbf{u}]_T^2)^p. \end{aligned}$$

Since  $\frac{N}{2q_2} + \frac{1}{2} < 1$  as follows from  $q_2 > N$ , by Hölder's inequality,

$$\begin{aligned} < t >^b III_\infty(t) &\leq C \int_{t-1}^t (t-s)^{-\frac{N}{2q_2}-\frac{1}{2}} < s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)} ds \\ &\leq C \left( \int_{t-1}^t (t-s)^{-\frac{N}{2q_2}-\frac{1}{2}} ds \right)^{1/p'} \left( \int_{t-1}^t (t-s)^{-\frac{N}{2q_2}-\frac{1}{2}} (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)})^p ds \right)^{1/p} \\ &\leq C \left( \frac{N}{2q_2} - \frac{1}{2} \right)^{-1/p'} \left( \int_{t-1}^t (t-s)^{-\frac{N}{2q_2}-\frac{1}{2}} (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)})^p ds \right)^{1/p}. \end{aligned}$$

By the change of integration order, we have

$$\begin{aligned} \int_2^T (< t >^b III_\infty(t))^p dt &\leq C \left( 1 - \frac{N}{2q_2} \right)^{-\frac{p}{p'}} \int_2^T dt \int_{t-1}^t (t-s)^{-\frac{N}{2q_2}-\frac{1}{2}} (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)})^p ds \\ &\leq C \left( 1 - \frac{N}{2q_2} \right)^{-\frac{p}{p'}} \int_1^T (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)})^p ds \int_s^{s+1} (t-s)^{-\frac{N}{2q_2}-\frac{1}{2}} dt \\ &= C \left( 1 - \frac{N}{2q_2} \right)^{-p} (\mathcal{I} + [\mathbf{u}]_T^2)^p. \end{aligned}$$

Summing up, we have obtained (57).

We next prove (58). By (56) with  $r = q_1$ ,  $\tilde{q}_1 = q_1/2$  and  $\tilde{q}_2 = q_1$ ,

$$\|\mathbf{v}(\cdot, t)\|_{L_{q_1}(\Omega)} \leq C(I_{q_1, \infty}(t) + II_{q_1, 1}(t) + III_{q_1, 1}(t))$$

with

$$\begin{aligned} I_{q_1, 1}(t) &= \int_0^{t/2} (t-s)^{-\frac{N}{2q_1}} \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds, \\ II_{q_1, 1}(t) &= \int_{t/2}^{t-1} (t-s)^{-\frac{N}{2q_1}} \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds, \\ III_{q_1, 1}(t) &= \int_{t-1}^t \|\mathbf{w}(\cdot, s)\|_{L_{q_1}(\Omega)} ds. \end{aligned}$$

By (54)

$$\begin{aligned} I_{q_1, 1}(t) &\leq (t/2)^{-\frac{N}{2q_1}} \left( \int_0^{t/2} < s >^{-bp'} ds \right)^{1/p'} \left( \int_0^T (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)})^p ds \right)^{1/p} \\ &\leq Ct^{-\frac{N}{2q_1}} (\mathcal{I} + [\mathbf{u}]_T^2). \end{aligned}$$

Analogously, by Hölder's inequality and (54),

$$\begin{aligned} II_{q_1, 1}(t) &\leq C \int_{t/2}^{t-1} (t-s)^{-\frac{N}{2q_1}} < s >^{-b} < s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds \\ &\leq C < t >^{-b} \left( \int_{t/2}^{t-1} (t-s)^{-\frac{N}{2q_1}} ds \right)^{1/p'} \left( \int_0^T (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)})^p ds \right)^{1/p} \end{aligned}$$



$$\begin{aligned}
&= C \left(1 - \frac{Np'}{2q_1}\right)^{1/p'} < t >^{-b - \frac{N}{2q_1} + \frac{1}{p'}} (\mathcal{I} + [\mathbf{u}]_T^2) \\
&\leq C \left(1 - \frac{Np'}{2q_1}\right)^{1/p'} < t >^{-\frac{N}{2q_1}} (\mathcal{I} + [\mathbf{u}]_T^2),
\end{aligned}$$

because  $b > \frac{1}{p'}$ . Finally, by (54),

$$\begin{aligned}
III_{q_1,1}(t) &\leq Ct^{-b} \int_{t-1}^t < s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds \\
&\leq Ct^{-b} \left( \int_{t-1}^t ds \right)^{1/p'} \left( \int_0^T (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)})^p ds \right)^{1/p} \\
&\leq Ct^{-b} (\mathcal{I} + [\mathbf{u}]_T^2).
\end{aligned}$$

Summing up, we have obtained (58).

We next prove (59). By (56),

$$\|\mathbf{v}(\cdot, t)\|_{H_{q_1}^1(\Omega)} \leq C(I_{q_1,2}(t) + II_{q_1,2}(t) + III_{q_1,2}(t))$$

with

$$\begin{aligned}
I_{q_1,2}(t) &= \int_0^{t/2} (t-s)^{-\frac{N}{2q_1}} \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds, \\
II_{q_1,2}(t) &= \int_{t/2}^{t-1} (t-s)^{-\frac{N}{2q_1}} \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds, \\
III_{q_1,2}(t) &= \int_{t-1}^t (t-s)^{-\frac{1}{2}} \|\mathbf{w}(\cdot, s)\|_{L_{q_1}(\Omega)} ds.
\end{aligned}$$

By (54),

$$\begin{aligned}
I_{q_1,2}(t) &\leq (t/2)^{-\frac{N}{2q_1}} \left( \int_0^{t/2} < s >^{-bp'} ds \right)^{1/p'} \left( \int_0^{t/2} (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)})^p ds \right)^{1/p} \\
&\leq Ct^{-\frac{N}{2q_1}} (\mathcal{I} + [\mathbf{u}]_T^2),
\end{aligned}$$

and so, by the condition:  $(\frac{N}{q_1} - b)p > 1$  in (19)

$$\left( \int_2^T (< t >^{b - \frac{N}{2q_1}} I_{q_1,2}(t))^p dt \right)^{1/p} \leq C \left( \left( \frac{N}{q_1} - b \right) p - 1 \right)^{-1/p} (\mathcal{I} + [\mathbf{u}]_T^2).$$

By Hölder's inequality,

$$\begin{aligned}
< t >^{b - \frac{N}{2q_1}} II_{q_1,2}(t) &\leq C < t >^{-\frac{N}{2q_1}} \int_{t/2}^{t-1} (t-s)^{-\frac{N}{2q_1}} < s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds \\
&\leq C < t >^{-\frac{N}{2q_1}} \left( \int_{t/2}^{t-1} (t-s)^{-\frac{Np'}{2q_1}} ds \right)^{1/p'} \left( \int_0^T (< s >^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)})^p ds \right)^{1/p} \\
&\leq C(1+t)^{-\left(\frac{N}{q_1} - \frac{1}{p'}\right)} (\mathcal{I} + [\mathbf{u}]_T^2).
\end{aligned}$$

Since  $(\frac{N}{q_1} - \frac{1}{p'})p > 1$  as follows from  $\frac{N}{q_1} = 1 + \frac{N}{q_2} > 1 = \frac{1}{p} + \frac{1}{p'}$ , we have

$$\left( \int_2^T (< t >^{b - \frac{N}{2q_1}} II_{q_1,2}(t))^p dt \right)^{1/p} \leq C \left( \left( \frac{N}{q_1} - b \right) p - 1 \right)^{-1/p} (\mathcal{I} + [\mathbf{u}]_T^2).$$

Since  $q_1/2 < q_1 < q_2$ , we have

$$\|\mathbf{w}(\cdot, t)\|_{L_{q_1}(\Omega)} \leq \|\mathbf{w}(\cdot, t)\|_{L_{q_1/2}(\Omega)}^{\frac{q_2}{N+2q_2}} \|\mathbf{w}(\cdot, t)\|_{L_{q_2}(\Omega)}^{\frac{N+q_2}{N+2q_2}}.$$

Let  $\alpha = \frac{q_2}{N+2q_2}$  and  $\beta = \frac{N+q_2}{N+2q_2}$ , and then  $\alpha + \beta = 1$ , and so, by (54) and Hölder's inequality

$$\begin{aligned}
& \| < t >^b \mathbf{w} \|_{L_p((0,T), L_{q_1}(\Omega))} \\
& \leq \left( \int_0^T (< t >^b \| \mathbf{w}(\cdot, t) \|_{L_{q_1/2}(\Omega)})^{p\alpha} (< t >^b \| \mathbf{w}(\cdot, t) \|_{L_{q_2}(\Omega)})^{p\beta} dt \right)^{1/p} \\
& \leq \left( \int_0^T (< t >^b \| \mathbf{w}(\cdot, t) \|_{L_{q_1/2}(\Omega)})^p dt \right)^{\alpha/p} \left( \int_0^T (< t >^b \| \mathbf{w}(\cdot, t) \|_{L_{q_2}(\Omega)})^p dt \right)^{\beta/p} \\
& \leq C(\mathcal{I} + [\mathbf{u}]_T^2).
\end{aligned} \tag{61}$$

Since

$$\begin{aligned}
< t >^{b-\frac{N}{2q_1}} III_{q_1,2}(t) & \leq \int_{t-1}^t (t-s)^{-\frac{1}{2}} < s >^{b-\frac{N}{2q_1}} \| \mathbf{w}(\cdot, s) \|_{L_{q_1}(\Omega)} ds \\
& \leq \left( \int_{t-1}^t (t-s)^{-\frac{1}{2}} ds \right)^{1/p'} \left( \int_{t-1}^t (t-s)^{-\frac{1}{2}} (< s >^b \| \mathbf{w}(\cdot, s) \|_{L_{q_1}(\Omega)})^p ds \right)^{1/p},
\end{aligned}$$

by the change of integration order, we have

$$\begin{aligned}
\int_2^T (< t >^{b-\frac{N}{2q_1}} III_{q_1,2}(t))^p dt & \leq 2^{\frac{p}{p'}} \int_2^T dt \int_{t-1}^t (t-s)^{-\frac{1}{2}} (< s >^b \| \mathbf{w}(\cdot, s) \|_{L_{q_1}(\Omega)})^p ds \\
& \leq 2^{\frac{p}{p'}} \int_0^T (< s >^b \| \mathbf{w}(\cdot, s) \|_{L_{q_1}(\Omega)})^p ds \int_s^{s+1} (t-s)^{-\frac{1}{2}} dt = 2^p \| < t >^b \mathbf{w} \|_{L_p((0,T), L_{q_1}(\Omega))},
\end{aligned}$$

which, combined with (61), leads to

$$\left( \int_2^T (< t >^{b-\frac{N}{2q_1}} III_{q_1,2}(t))^p dt \right)^{1/p} \leq C(\mathcal{I} + [\mathbf{u}]_T^2).$$

Summing up, we have obtained (59).

We finally prove (60). By (56) with  $r = q_2$ ,  $\tilde{q}_1 = q_1/2$  and  $\tilde{q}_2 = q_2$ ,

$$\| \mathbf{v}(\cdot, t) \|_{L_{q_2}(\Omega)} \leq C(I_{q_2}(t) + II_{q_2}(t) + III_{q_2}(t))$$

with

$$\begin{aligned}
I_{q_2}(t) &= \int_0^{t/2} (t-s)^{-\frac{N}{2}(\frac{2}{q_1}-\frac{1}{q_2})} \| \mathbf{w}(\cdot, s) \|_{L_{q_1/2}(\Omega)} ds, \\
II_{q_2}(t) &= \int_{t/2}^{t-1} (t-s)^{-\frac{N}{2}(\frac{2}{q_1}-\frac{1}{q_2})} \| \mathbf{w}(\cdot, s) \|_{L_{q_1/2}(\Omega)} ds, \\
III_{q_2}(t) &= \int_{t-1}^t \| \mathbf{w}(\cdot, s) \|_{L_{q_2}(\Omega)} ds.
\end{aligned}$$

By Hölder's inequality,

$$\begin{aligned}
I_{q_2}(t) & \leq (t/2)^{-\frac{N}{2}(\frac{2}{q_1}-\frac{1}{q_2})} \left( \int_0^{t/2} < s >^{-bp'} ds \right)^{1/p'} \left( \int_0^{t/2} (< s >^b \| \mathbf{w}(\cdot, s) \|_{L_{q_1/2}(\Omega)})^p ds \right)^{1/p} \\
& \leq C < t >^{-\frac{N}{2}(\frac{2}{q_1}-\frac{1}{q_2})} (\mathcal{I} + [\mathbf{u}]_T^2)
\end{aligned}$$

for  $t \geq 2$ . Since

$$\frac{N}{2} \left( \frac{2}{q_1} - \frac{1}{q_2} \right) - \left( b - \frac{N}{2q_2} \right) = \frac{N}{q_1} - b,$$

by the condition:  $(\frac{N}{q_1} - b)p > 1$  in (19),

$$\left( \int_2^T (< t >^{b-\frac{N}{2q_2}} I_{q_2}(t))^p dt \right)^{1/p} \leq C \left( \int_2^T t^{-(\frac{N}{q_1}-b)p} dt \right)^{1/p} (\mathcal{I} + [\mathbf{u}]_T^2)$$

$$\leq C \left( \left( \frac{N}{q_1} - b \right) p - 1 \right)^{-1/p} (\mathcal{I} + [\mathbf{u}_T^2]).$$

Since

$$\frac{N}{2} \left( \frac{2}{q_1} - \frac{1}{q_2} \right) = \frac{N}{2} \left( \frac{1}{q_2} + \frac{2}{N} \right) = \frac{N}{2q_2} + 1 > 1,$$

by Hölder's inequality

$$\begin{aligned} \langle t \rangle^{b - \frac{N}{2q_2}} II_{q_2}(t) &\leq C \int_{t/2}^{t-1} (t-s)^{-\left(\frac{N}{2q_2}+1\right)} \langle s \rangle^{b - \frac{N}{2q_2}} \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)} ds \\ &\leq C \left( \int_{t/2}^{t-1} (t-s)^{-\left(\frac{N}{2q_2}+1\right)} ds \right)^{1/p'} \left( \int_{t/2}^{t-1} (t-s)^{-\left(\frac{N}{2q_2}+1\right)} \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)}^p ds \right)^{1/p} \\ &\leq C \left( \frac{N}{2q_2} \right)^{-1/p'} \left( \int_{t/2}^{t-1} (t-s)^{-\left(\frac{N}{2q_2}+1\right)} \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)}^p ds \right)^{1/p}, \end{aligned}$$

and so, by the change of integration order and (54)

$$\begin{aligned} \int_2^T \langle t \rangle^{b - \frac{N}{2q_2}} II_{q_2}(t)^p dt &\leq C \left( \frac{N}{2q_2} \right)^{-p/p'} \int_2^T dt \int_{t/2}^{t-1} (t-s)^{-\left(\frac{N}{2q_2}+1\right)} \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)}^p ds \\ &\leq C \left( \frac{N}{2q_2} \right)^{-p/p'} \int_0^T \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_1/2}(\Omega)}^p ds \int_{s+1}^{2s} (t-s)^{-\left(\frac{N}{2q_2}+1\right)} dt \leq C \left( \frac{N}{2q_2} \right)^{-p} (\mathcal{I} + [\mathbf{u}_T^2])^p. \end{aligned}$$

Analogously, by Hölder's inequality

$$\begin{aligned} \langle t \rangle^{b - \frac{N}{2q_2}} III_{q_2}(t) &\leq C \int_{t-1}^t \langle s \rangle^{b - \frac{N}{2q_2}} \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)} ds, \\ &\leq C \left( \int_{t-1}^t ds \right)^{1/p'} \left( \int_{t-1}^t \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)}^p ds \right)^{1/p} \\ &= C \left( \int_{t-1}^t \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)}^p ds \right)^{1/p}, \end{aligned}$$

and so, by the change of integration order and (54)

$$\begin{aligned} \int_2^T \langle t \rangle^{b - \frac{N}{2q_2}} III_{q_2}(t)^p dt &\leq C \int_2^T dt \int_{t-1}^t \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)}^p ds \\ &\leq C \int_0^T \langle s \rangle^b \|\mathbf{w}(\cdot, s)\|_{L_{q_2}(\Omega)}^p ds \int_s^{s+1} dt \leq C (\mathcal{I} + [\mathbf{u}_T^2])^p. \end{aligned}$$

Summing up, we have obtained (60).

Recalling that  $T \geq 2$ , applying the maximal  $L_p$ - $L_q$  regularity theorem due to Shibata [9] to Eq. (53) and using (54) give that

$$\|\mathbf{v}\|_{L_p((0,2), H_q^2(\Omega))} + \|\partial_t \mathbf{v}\|_{L_p((0,2), L_q(\Omega))} \leq C_q \|\lambda_0 \mathbf{w}\|_{L_p((0,2), L_q(\Omega))} \leq C (\mathcal{I} + [\mathbf{u}_T^2]) \quad (62)$$

for any  $q \in [q_1/2, q_2]$ . Thus, by real interpolation, we have

$$\sup_{0 < t < 2} \|\mathbf{v}(\cdot, t)\|_{B_{q,p}^{2(1-1/p)}(\Omega)} \leq C (\|\mathbf{v}\|_{L_p((0,2), H_q^2(\Omega))} + \|\partial_t \mathbf{v}\|_{L_p((0,2), L_q(\Omega))}) \leq C_q (\mathcal{I} + [\mathbf{u}_T^2]) \quad (63)$$

for any  $q \in [q_1/2, q_2]$ . Combining (57), (58), (59), (60), (62), (63) and the Sobolev imbedding theorem, we have

$$\begin{aligned} \|\langle t \rangle^b \mathbf{v}\|_{L_p((0,T), H_\infty^1(\Omega))} + \|\langle t \rangle^{\frac{N}{2q_1}} \mathbf{v}\|_{L_\infty((0,T), L_{q_1}(\Omega))} \\ + \|\langle t \rangle^{b - \frac{N}{2q_1}} \mathbf{v}\|_{L_p((0,T), H_{q_1}^1(\Omega))} + \|\langle t \rangle^{b - \frac{N}{2q_2}} \mathbf{v}\|_{L_p((0,T), L_{q_2}(\Omega))} \leq C (\mathcal{I} + [\mathbf{u}_T^2]). \end{aligned} \quad (64)$$

From (53),  $\mathbf{v}$  satisfies the equations:

$$\begin{cases} \partial_t \mathbf{v} + \lambda_0 \mathbf{v} - J(T)^{-1} \text{Div} \tilde{\mathbf{S}}(\mathbf{v}, \mathbf{p}) = -\lambda_0 \mathbf{w} + \lambda_0 \mathbf{v} & \text{in } \Omega \times (0, T), \\ \text{div } \mathbf{v} = 0 & \text{in } \Omega \times (0, T), \\ \tilde{\mathbf{S}}(\mathbf{v}, \mathbf{p}) = 0 & \text{on } \Gamma \times (0, T), \\ \mathbf{v}|_{t=0} = 0 & \text{in } \Omega, \end{cases}$$

and so by (49) we have

$$\begin{aligned} & \| < t >^{b-\frac{N}{2q_2}} \mathbf{v} \|_{L_p((0,T), H_{q_2}^2(\Omega))} + \| < t >^{b-\frac{N}{2q_2}} \partial_t \mathbf{v} \|_{L_p((0,T), L_{q_2}(\Omega))} \\ & \leq C \| < t >^{b-\frac{N}{2q_2}} (\mathbf{v}, \mathbf{w}) \|_{L_p((0,T), L_{q_2}(\Omega))}, \end{aligned}$$

which, combined with (64), leads to

$$[\mathbf{v}]_T \leq C(\mathcal{I} + [\mathbf{u}]_T^2). \quad (65)$$

Since  $\mathbf{u} = \mathbf{w} + \mathbf{v}$ , by (54) and (65), we see that  $\mathbf{u}$  satisfies the inequality (51), which completes the proof of Theorem 1.

## 2 Two Phase Problem

Let  $\Omega_+$  be a bounded domain in  $\mathbb{R}^N$  and  $\Gamma$  its boundary that is a smooth compact hypersurface. Let  $\Omega_- = \mathbb{R}^N \setminus \overline{\Omega}_+$  and two different incompressible viscous fluids occupy  $\Omega_\pm$ , respectively. Let  $\Omega_{\pm t}$  and  $\Gamma_t$  be the time evolution of  $\Omega_\pm$  and  $\Gamma$  for  $t > 0$ . Let  $\mathbf{n}_t$  be the unit outer normal to  $\Gamma_t$ . Problem is to find domains  $\Omega_{\pm t}$ , velocities  $\mathbf{v}_\pm = (v_{1\pm}, \dots, v_{N\pm})$  and pressures  $\mathbf{p}_\pm$  satisfying the Navier-Stokes equations:

$$\begin{cases} \partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{v} - \text{Div}(\mu \mathbf{D}(\mathbf{v}) - \mathbf{p} \mathbf{I}) = 0, \quad \text{div } \mathbf{v} = 0 & \text{in } \Omega_t \text{ for } t \in (0, T), \\ [[\mu \mathbf{D}(\mathbf{v}) - \mathbf{p} \mathbf{I}]] \mathbf{n}_t = \sigma H(\Gamma_t) \mathbf{n}_t, \quad [[\mathbf{v}]] = 0, \quad V_{\Gamma_t} = \mathbf{v} \cdot \mathbf{n}_t & \text{on } \Gamma_t \text{ for } t \in (0, T), \\ \mathbf{v}|_{t=0} = \mathbf{v}_0 & \text{in } \Omega_0 = \Omega. \end{cases} \quad (66)$$

Here,  $\Omega_t = \Omega_{+t} \cup \Omega_{-t}$ ,  $\Omega = \Omega_+ \cup \Omega_-$ ,  $h = h_\pm$  for  $x \in \Omega_{\pm t}$ ,  $\mu = \mu_\pm$  for  $x \in \Omega_{\pm t}$ ,  $\mu_\pm$  being positive constants representing viscosity coefficients,  $\sigma$  positive constant (coefficient of surface tension),  $H(\Gamma_t)$   $N-1$  times the mean curvature of  $\Gamma_t$ ,  $V_{\Gamma_t}$  the evolution speed of  $\Gamma_t$  in the  $\mathbf{n}_t$  direction,  $\mathbf{I}$  the  $N \times N$  identity matrix,  $\mathbf{D}(\mathbf{v}) = \nabla \mathbf{v} + (\nabla \mathbf{v})^\top$  the doubled deformation tensor whose  $(i, j)^{\text{th}}$  component is  $\partial_i v_j + \partial_j v_i$ , and  $[[f]](x_0) = \lim_{\substack{x \rightarrow x_0 \\ x \in \Omega_+}} f(x) - \lim_{\substack{x \rightarrow x_0 \\ x \in \Omega_-}} f(x)$ , which is the jump quantity of  $f$  at  $x_0 \in \Gamma_t$ .

This problem has been studied by the following authors:

- V. Denisova, V. A. Solonnikov [1], [2] in the  $L_2$  frame work and the Hölder space framework.
- J. Pruess et al [3], [4], [5], [6],  $L_p$  maximal regularity and Local well-posedness. Global well-posedness in the container by the combination of  $L_p$ -maximal regularity with Spectral analysis for the Laplace- Bertrami operator.

But, the global well-posedness in unbounded domains has not yet been studied well. In this note, the global well-posedness results are announced in the case that  $\sigma = 0$  and  $\sigma > 0$ .

First of all, we mention that **Maximal  $L_p$ - $L_q$  regularity** for the two phase problem for the Stokes equations does hold in a uniformly  $C^2$  ( $\sigma = 0$  case) or  $C^3$  ( $\sigma > 0$  case) domain under the assumption that weak Neumann problem is uniquely solvable (cf. Pruess et al [3, 4, 5, 6], Shibata and Shimizu [12], and Maryani and Saito [7]). Thus, **Local well-posedness** holds. Here, it is important that  $p$  and  $q$  can be chosen differently to prove Global well-posedness for free boundary problem in an unbounded domain. In fact as was seen in Sect. 1, in the unbounded domain case, we can get only polynomial decay properties for suitable  $L_q$  space norm of solutions, and so we have to choose  $p$  rather large to guarantee the  $L_p$  summability in time.

## 2.1 Global wellposedness, $\sigma > 0$ case

Let  $B_R = \{x \in \mathbb{R}^N \mid |x| < R\}$  and  $S_R = \{x \in \mathbb{R}^N \mid |x| = R\}$ . We assume that

**Assumption 1**  $|\Omega_+| = |B_R| = R^N \omega_N / N$ , where  $|\cdot|$  denotes the Lebesgue measure and  $\omega_N$  is the area of the unit sphere.

**Assumption 2**  $\int_{\Omega} x \, dx = 0$ .

**Assumption 3**  $\Gamma = \{x = (R + \rho_0(R\omega))\omega \mid \omega \in S_1\}$  with given small function  $\rho_0$  defined on  $S_R$ .  
Let

$$\Gamma_t = \{x = (R + \rho(R\omega, t))\omega + \xi(t) \mid \omega \in S_1\}$$

where  $\rho$  is an unknown function and  $\xi(t)$  is the barycenter point of the domain  $\Omega_t$  defined by

$$\xi(t) = \frac{1}{|\Omega_+|} \int_{\Omega_+} x \, dx.$$

Assume that  $\Omega_+ \subset B_R$  with a large constant  $R > 0$ . Let  $L \geq 3R$ . Given  $\rho \in W_q^{3-1/q}(S_R)$ , let  $H(\xi, t) \in H_q^3(\dot{B}_L)$  be a function such that  $H|_{S_R} = R^{-1}\rho$ ,  $\|H\|_{H_q^2(\dot{B}_L)} \leq C\|\rho\|_{W_q^{2-1/q}(S_R)}$ , and  $\|H\|_{H_q^3(\dot{B}_L)} \leq C\|\rho\|_{W_q^{3-1/q}(S_R)}$ , where  $\dot{B}_L = B_L \setminus S_R$ .

Let  $\varphi \in C_0^\infty(\mathbb{R}^N)$  such that  $\varphi(x) = 1$  for  $|x| \leq L - 2$  and  $\varphi(x) = 0$  for  $|x| \geq L - 1$ . We use the **Hanzawa transform** defined by

$$x = e_h(y, t) = y + \varphi(y)H(y, t)y + \xi(t) \quad \text{for } y \in B_R.$$

Let

$$\begin{aligned} \mathbf{u}(y, t) &= \mathbf{v} \circ e_h, \quad \mathbf{q}(y, t) = \mathbf{p} \circ e_h - \frac{(N-1)\sigma}{R}. \\ \Omega_t &= \{x = y + \varphi(y)H(y, t)y + \xi(t) \mid y \in B_R\}, \quad \Gamma_t = \{x = (R + \rho(R\omega, t))\omega \mid \omega \in S_1\}. \end{aligned}$$

And then, problem (66) is transformed to

$$\left\{ \begin{array}{ll} \partial_t \mathbf{u} - \text{Div}(\mu \mathbf{D}(\mathbf{u}) - \mathbf{q} \mathbf{I}) = F(\mathbf{u}, H) & \text{in } \Omega \times (0, T), \\ \text{div } \mathbf{u} = F_d(\mathbf{u}, H) = \text{div } \mathbf{F}_d(\mathbf{u}, H) & \text{in } \Omega \times (0, T), \\ [[\mu \mathbf{D}(\mathbf{u}) - \mathbf{q}]]\omega - \sigma(B_R \rho)\mathbf{n} = G(\mathbf{u}, \rho), \quad [[\mathbf{u}]] = 0 & \text{in } S_R \times (0, T), \\ \partial_t \rho - \mathbf{n} \cdot P\mathbf{u} = D(\mathbf{u}, \rho) & \text{on } S_R \times (0, T), \\ (\mathbf{u}, \rho)|_{t=0} = (\mathbf{u}_0, \rho_0) & \text{on } \Omega \times S_R. \end{array} \right. \quad (67)$$

Here,  $\Omega = B_R \cup B^R$  with  $B^R = \{x \in \mathbb{R}^N \mid |x| > R\}$ ,  $\mathbb{R}^N = \Omega \cup S_R$ ,

$$B_R \rho = R^{-2}(\Delta_{S_1} + N - 1)\rho, \quad P\mathbf{u} = \mathbf{u} - \frac{1}{|B_R|} \int_{B_R} \mathbf{u}(y) \, dy.$$

$\Delta_{S_1}$  is the Laplace-Beltrami operator on  $S_1$ , and  $F(\mathbf{u}, H)$ ,  $F_d(\mathbf{u}, H)$ ,  $\mathbf{F}_d(\mathbf{u}, H)$ ,  $D(\mathbf{u}, \rho)$  are nonlinear functions. Then, we have the following theorem that is our global well-posedness theorem in the case that  $\sigma > 0$ .

**Theorem 14.** *Let  $N \geq 3$ . Let  $q_1$  and  $q_2$  be exponents such that  $N < q_2 < \infty$  and  $1/q_1 = 1/q_2 + 1/N$ . Let  $b$  be a number such that  $N/q_1 > b \geq N/(2q_2)$ . Then, there exists an  $\epsilon > 0$  such that if initial data  $\mathbf{u}_0 \in B_{q_2, p}^{2(1-1/p)} \cap B_{q_1/2, p}^{2(1-1/p)} = D_{p, q_1, q_2}$  and  $\rho_0 \in B_{q_2, p}^{3-1/p-1/q_2}(S_R)$  satisfy the smallness condition:*

$$\|\mathbf{u}_0\|_{D_{p, q_1, q_2}} + \|\rho_0\|_{B_{q_2, p}^{3-1/p-1/q_2}(S_R)} \leq \epsilon$$

and the compatibility condition:

$$\text{div } \mathbf{u}_0 = 0 \text{ in } \Omega, \quad [[\mu \mathbf{D}(\mathbf{u}_0)]]\omega - [[[\mu \mathbf{D}(\mathbf{u}_0)]]\omega, \omega] = 0 \text{ on } S_R,$$

then problem (67) admits unique solutions  $\mathbf{u}$  and  $\rho$  with

$$\begin{aligned} \mathbf{u} &\in L_p((0, \infty), H_{q_2}^2(\Omega)^N \cap H_{q_1/2}^2(\Omega)^N) \cap H_p^1((0, \infty), L_{q_2}(\Omega)^N \cap L_{q_1/2}(\Omega)^N), \\ \rho &\in L_p((0, \infty), W_{q_2}^{3-1/q_2}(S_R)) \cap H_p^1((0, \infty), W_{q_2}^{2-1/q_2}(S_R)) \end{aligned}$$

possessing the estimate:  $E(\mathbf{u}, \rho)(0, \infty) \leq C\epsilon$ . Here,

$$\begin{aligned} E(\mathbf{u}, \rho)(0, T) &= \| \langle t \rangle^b (\mathbf{u}, H) \|_{L_\infty((0, T), H_\infty^1(\Omega) \times H_\infty^2(\dot{B}_L))} + \| \langle t \rangle^{b-\frac{N}{2q_1}} \mathbf{u} \|_{L_p((0, T), H_{q_1}^1(\Omega))} \\ &+ \| \langle t \rangle^{\frac{N}{2q_1}} \mathbf{u} \|_{L_\infty((0, T), L_{q_1}(\Omega))} + \| \langle t \rangle^{b-\frac{N}{2q_2}} \partial_t(\mathbf{u}, H) \|_{L_p((0, T), L_{q_2}(\Omega) \times H_{q_2}^2(\dot{B}_L))} \\ &+ \| \langle t \rangle^{b-\frac{N}{2q_2}} (\mathbf{u}, H) \|_{L_p((0, T), H_{q_2}^2(\Omega) \times H_{q_2}^3(\dot{B}_L))}. \end{aligned}$$

Here,  $\langle t \rangle = (1 + t^2)^{1/2}$ .

## 2.2 Global wellposedness, $\sigma = 0$ case

In this case, we can not use the Hanzawa transform, because of the lack of regularity for the height function  $\rho$ . Thus, we use the partial Lagrange transform like Sect. 1. Let  $\varphi \in C_0^\infty(\mathbb{R}^N)$  such that  $\varphi(x) = 1$  for  $|x| \leq L - 2$  and  $\varphi(x) = 0$  for  $|x| \geq L - 1$  for  $L \geq 3R$ . Let  $\mathbf{u}(\xi, s) = \mathbf{u}_\pm(\xi, s)$  for  $\xi \in \Omega_\pm$  be the Lagrange velocity fields, and the partial Lagrange transform is defined by

$$x = \xi + \varphi(\xi) \int_0^t \mathbf{u}(\xi, s) ds = X_{\mathbf{u}}(\xi, t) \quad \text{for } \xi \in \Omega_\pm.$$

There exists a small constant  $\sigma > 0$  such that if

$$\int_0^T \|\nabla(\varphi(\cdot) \mathbf{u}(\cdot, s))\|_{L_\infty(\Omega)} ds \leq \sigma$$

then, the partial Lagrange transform is a diffeomorphism from  $\Omega = \Omega_+ \cup \Omega_- = \mathbb{R}^N \setminus \Gamma$  onto  $\Omega_t = \{x = X_{\mathbf{u}}(\xi, t) \mid \xi \in \Omega\}$ .

By the partial Lagrange transform, problem (66) is transformed to

$$\begin{cases} \partial_t \mathbf{u} - \text{Div}(\mu \mathbf{D}(\mathbf{u}) - \mathbf{q} \mathbf{I}) = F(\mathbf{u}), & \text{div } \mathbf{v} = f(\mathbf{u}) = \text{div } \mathbf{f}(\mathbf{u}) & \text{in } \Omega \times (0, T), \\ [[\mu \mathbf{D}(\mathbf{u}) - \mathbf{q} \mathbf{I}]] \mathbf{n} = \mathbf{g}(\mathbf{u}), & [[\mathbf{u}]] = 0 & \text{on } \Gamma \times (0, T), \\ \mathbf{u}|_{t=0} = \mathbf{v}_0, & \Omega_t|_{t=0} = \Omega, \end{cases} \quad (68)$$

with suitable nonlinear functions  $F(\mathbf{u})$ ,  $f(\mathbf{u})$ ,  $\mathbf{f}(\mathbf{u})$  and  $\mathbf{g}(\mathbf{u})$ . Then, we have the following theorem.

**Theorem 15.** Let  $N \geq 3$  and let  $q_1$  and  $q_2$  be exponents such that  $N < q_2 < \infty$  and  $1/q_1 = 1/q_2 + 1/N$  and  $q_1 > 2$ . Let  $b$ ,  $p$  and  $p' = p/(p-1)$  be numbers satisfying the conditions:

$$\begin{aligned} \frac{N}{q_1} &> b > \frac{1}{p'}, \quad \left(\frac{N}{q_1} - b\right)p > 1, \quad \left(b - \frac{N}{2q_2}\right)p > 1, \quad b > \frac{N}{2q_1}, \\ \left(\frac{N}{2q_2} + \frac{1}{2}\right)p' &< 1, \quad bp' > 1, \quad \left(b - \frac{N}{2q_2}\right)p' > 1, \quad \frac{N}{q_2} + \frac{2}{p} < 1. \end{aligned} \quad (69)$$

Then, there exists an  $\epsilon > 0$  such that if initial data  $\mathbf{v}_0$  satisfies the compatibility condition and the smallness condition:  $\|\mathbf{v}_0\|_{B_{q_2, p}^{2(1-1/p)}(\Omega)} + \|\mathbf{v}_0\|_{B_{q_1/2, p}^{2(1-1/p)}(\Omega)} \leq \epsilon$ , then problem (68) admits a unique solution  $\mathbf{u} \in L_p((0, \infty), H_{q_2}^2(\Omega)^N) \cap H_p^1((0, \infty), L_{q_2}(\Omega)^N)$ , possessing the estimate:  $[\mathbf{u}]_\infty < C\epsilon$  with some constant  $C > 0$  independent of  $\epsilon$ . Here

$$\begin{aligned} [\mathbf{u}]_T &= \left\{ \int_0^T ((1+t)^b \|\mathbf{u}(\cdot, s)\|_{H_\infty^1(\Omega)})^p ds \right. \\ &+ \int_0^T ((1+s)^{(b-\frac{N}{2q_1}}) \|\mathbf{u}(\cdot, s)\|_{H_{q_1}^1(\Omega)})^p ds + \left( \sup_{0 < s < T} (1+s)^{\frac{N}{2q_1}} \|\mathbf{u}(\cdot, s)\|_{L_{q_1}(\Omega)})^p \right. \\ &\left. + \int_0^T ((1+s)^{(b-\frac{N}{2q_2}}) (\|\mathbf{u}(\cdot, s)\|_{H_{q_2}^2(\Omega)} + \|\partial_t \mathbf{u}(\cdot, s)\|_{L_{q_2}(\Omega)}))^p ds \right\}^{1/p}. \end{aligned}$$

**Remark 16.** We can prove Theorem 15 by using the similar argument to that in Sect. 1.

## References

- [1] V. Denisova, *Global  $L_2$ -solvability of a problem governing two-phase fluid motion without surface tension*, Portugal Math. (N.S.) **71** (1) (2014), 1–24. DOI 10.4171/PM/1938.
- [2] V. Denisova and V. A. Solonnikov, *Global solvability of a problem governing the motion of two incompressible capillary fluids in a container*, J. Math. Sci., **185**(5) (2012), 668–686.
- [3] J. Prüss, S. Shimizu, and M. Wilke, *On the qualitative behaviour of incompressible two-phase flows with phase transition; The case of non-equal densities*, Commun. Partial Diff. Eqns., **39** (2014), 1236–1283.
- [4] J. Prüss and G. Simonett, *On the two-phase Navier-Stokes equations with surface tension*, Interfaces Free Bound., **12** (2010), 311–345.
- [5] J. Prüss and G. Simonett, *Analytic solutions for the two-phase Navier-Stokes equations with surface tension and gravity*, In: Parabolic Problems, pp. 507–540, Birkhäuser, Basel (2011).
- [6] J. Pruess and G. Simonett, *Moving Interfaces and Quasilinear Parabolic Evolution Equations*, Birkhauser Monographs in Mathematics, 2016. ISBN: 978-3-319-27698-4
- [7] S. Maryani and H. Saito, *On the  $\mathcal{R}$ -boundedness of solution operator families for two-phase Stokes resolvent equations*, Diff. Int. Eqns., **30** (1-2) (2017), 1–52.
- [8] Y. Shibata, *On the  $\mathcal{R}$ -bounded solution operators in the study of free boundary problem for the Navier-Stokes equations*, Springer Proceedings in Mathematics & Statistics Vol. 183 2016, Mathematical Fluid Dynamics, Present and Future Tokyo, Japan, November 2014, ed. Y. Shibata and Y. Suzuki, pp.203–285.
- [9] Y. Shibata, *Local wellposedness for the free boundary problem of the Navier-Stokes equations in an exterior domain*, Accepted for publication in Communication in Pure and Applied Analysis.
- [10] Y. Shibata, *On  $L_p$ - $L_q$  decay estimate for Stokes equations with free boundary condition in an exterior domain*, Accepted for publication in Asymptotic Analysis.
- [11] Y. Shibata, *Global wellposedness of a free boundary problem for the Navier-Stokes equations in an exterior domain*, Accepted for publication in Fluid Mechanics Research International Journal.
- [12] Y. Shibata and S. Shimizu, *Maximal  $L_p$ - $L_q$  regularity for the two-phase Stokes equations; model problems*, J. Differential Equations, **251** (2011), 373–419.